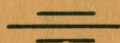
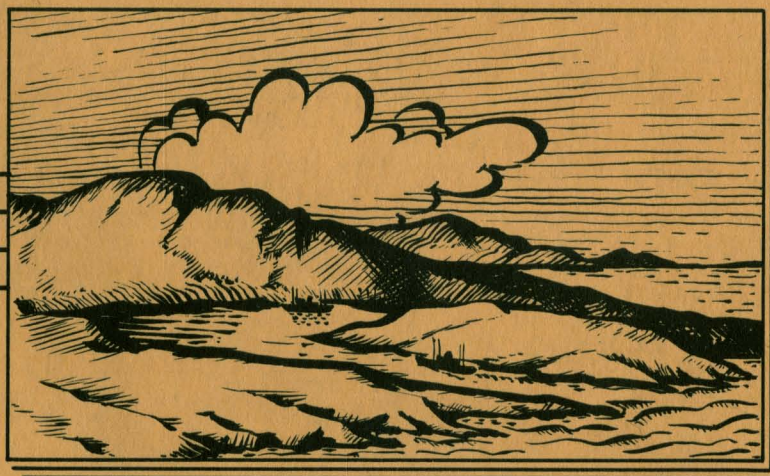


plowshare
Series



INDUSTRIAL USES
of
NUCLEAR EXPLOSIVES



University of California
Radiation Laboratory



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Contract No. W-7405-eng-48

INDUSTRIAL USES OF NUCLEAR EXPLOSIVES

PLOWSHARE
Series Report No. 1

Edited by
Harlan Zodtner

September 8, 1958

PREFACE

The first symposium on the Industrial Uses of Nuclear Explosives was organized by Harold Brown and held at the University of California Radiation Laboratory, Livermore, on February 6-8, 1957. The participants were employees or consultants of three AEC laboratories: the University of California Radiation Laboratory, the Los Alamos Scientific Laboratory, and the Sandia Corporation.

The original symposium report was prepared and edited by Roy Goranson of the University of California Radiation Laboratory. Since many of the ideas involved modifications or extensions of the technology on which weapons design is based, most of the papers had classified sections. In preparing this declassified version, the classified parts of the reports were removed or suitably modified. Some of the authors have taken this opportunity to include the results of the underground Rainier test (UCRL-5124). Even so, the thoughts presented here are now mostly two years old; some of them have been abandoned, some have been polished up, and only a few represent current thinking. Advances in nuclear explosive technology and phenomenology have reoriented some ideas and stimulated new ones. For instance, most of the excavation articles used nuclear explosives with a five percent fission-to-fusion ratio; for "landscaping" applications, a great deal of progress can be made toward reducing this ratio further.

A second symposium on Industrial Uses of Nuclear Explosives is now being planned on a completely unclassified basis and is tentatively scheduled to be held in San Francisco sometime in February 1959. The major topics will be similar to the ones in this report: power production, oil and mining applications, excavation projects, isotope production, and miscellaneous applications. There will also be one session on what has been learned in the underground detonations in Nevada.

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INTRODUCTION

by

Edward Teller (UCRL)

The question of nonmilitary uses of atomic energy has come up repeatedly; and I cannot give you a complete list, but some of the older suggestions are worthy of mention. One was that of Otto Frisch during the war, which was to use the neutrons from an atomic bomb. His suggestion was to pipe them out through a vacuum line so as to get the neutron spectrum free from scattering. A much later suggestion was made by John Wheeler, who proposed exploding thermonuclear devices deep under water and collecting the plutonium and other products. What I would like to mention now are topics which might otherwise be overlooked, and abstain from topics which will be discussed in more detail later on.

First of all I would like to take up the question "To what extent nuclear explosives for peaceful uses might differ from those for military uses?" It is obvious that some of the requirements for military uses need not be taken seriously when you are talking about peaceful uses. For example, when it is desired to place a bomb deep underground or on the surface of the earth, there is no reason to make it particularly light, although when it is desired to place it down in a deep hole, one might want to make it small. One might also consider high-explosive systems that do not economize on weight in order to make more economic use of fissionable material. Nuclear weapons have been developed such that they are now very efficient devices. Nuclear energy in the form of thermonuclear explosives should be available for a fraction of a mill per kilowatt-hour equivalent.

It is well known that approximately as much high explosive has been used for peaceful purposes as for use in war, and prior to World War II very much more high explosive had been used for peaceful purposes than for military purposes. That nuclear explosives have not been considered for peacetime use is, I think, due more to the radioactive material that they produce than to any other single reason. This should intensify the development of devices with a very low fission-to-fusion ratio.

One of the very hopeful possibilities is one which has already been mentioned, namely, production of materials. The materials that are produced will have to be contained in some way and afterwards collected.

Suggestions as to containment have been sea water, ice, or a blanket which is irradiated from above. An obvious use of thermonuclear devices is to make some additional valuable material by neutron capture. It is somewhat less obvious that material can be made by multiple neutron capture. An example of this is californium which has a lifetime of about 55 days for spontaneous fission. This spontaneous fission has one advantage as compared to other spontaneous processes in that it releases a respectable amount of energy. In fact, if californium is produced with the help of neutron capture, then in principle more energy will be produced from the fission than has been immediately released by the neutron capture. Fifty-five days is a short time so that one would have to collect californium very fast and it is easy to find objections to the idea; but when one has the material one could put it in a rather light system (not a clumsy one like a reactor) which would just perk away.

There have been a number of discussions on a topic which is somewhat related to power production and which may be called mining. The reason for the relation is that both power and mining will be associated with the explosion of nuclear devices deep underground, and therefore similar techniques will have to be used. The mineral referred to here is oil. There have been numerous suggestions as to how production may be increased by atomic explosions. The question of raising the pressure in a reservoir is a very important one in oil production. What is done in a well of decreasing productivity is to displace the oil by pumping in water. Now this, in essence, is fine except for a serious difficulty, which is that in displacing a viscous liquid by a less viscous liquid something akin to Taylor instability occurs wherein the nonviscous fluid finds its way into the viscous fluid, rather than pushing the viscous fluid ahead. This phenomenon, in the oil industry, is called "fingering." There seems to be a law of nature which says that all viscous fluids are expensive and therefore one cannot use this process as economically as one would desire.

Now it would seem not entirely impracticable to use a nonviscous fluid, namely, the gases produced by a nuclear explosion which push on a plug in front which is very viscous indeed, namely the rock. The nuclear explosive would be detonated under the reservoir making a cavity and raising the pressure in the general neighborhood. One might thereby

accomplish an objective, which the oil industry has tried to accomplish for a long time.

Another obvious class of uses is "landscaping." I have in mind such things as digging canals, making harbors, or removing obstacles. In this case a bomb with a low fission-to-fusion ratio is badly needed.

I should like now to talk of another field which is less practical but, to my mind, more interesting, namely, "How to use thermonuclear devices in research?" Let us start with Otto Frisch's idea. Suppose now we have a device exploded underground and connected with the surface by an open and straight channel. One could close the channel with high explosive before any jet or fissionable material comes out but after the neutrons come out. The advantage would be that one could construct a laboratory and make really elaborate counting equipment which will survive the experiment and which therefore can be built on a quite different and more efficient basis than such equipment has been built in past tests.

One might also hope to count neutrinos by placing a thermonuclear source underground, and the counting equipment above the surface or vice versa. The detector system should be at a distance such that it would receive a strong shock. It will therefore have to withstand the shock, recover, and be in a position to count at about 10 to 15 milliseconds after the shock has passed. There would be one advantage to this kind of procedure as compared to the successful experiment with the reactor, namely, that one can place emphasis on the fast neutrinos.

One could manage to attach a small, light nuclear device (it need not be a high-yield one) to a rocket and shoot it outside of the atmosphere. The x-rays from such an object, in addition to the neutrons, will give rise to some fluorescence around the object, and this fluorescence would be quite extended in space; in fact, the more extended the further it is out of the atmosphere. It might happen that this could be a reasonable way to study the density of gases at very great altitudes. We know much less about the density of matter in interplanetary space than we know about its average density in interstellar space. Densities of 10^7 or 10^8 particles per cubic centimeter down to one particle per cubic centimeter have been quoted. There is thus a very considerable uncertainty and, clearly, while it might be difficult to get experience about the lowest densities, one might

at least go up in the atmosphere in this way. A nice thing about this is that one has only to put up the test object and after that merely observe appropriately.

One will probably not long resist the temptation to shoot at the moon. The device might be set off relatively close to the moon and one would then look for the fluorescence coming off the lunar surface, or one might actually shoot right at the moon, try to observe what kind of disturbance it would cause, and ascertain what one can judge about the consistency of the lunar surface, perhaps down to some depth.

Finally all kinds of studies, such as spectroscopic, equation of state, hydrodynamics, etc., in the fireball open up a field of high-temperature physics with which we are all too unfamiliar.

FRESHMEN SUGGESTIONS

by

John A. Wheeler (Princeton University)

I asked for suggestions from my class, announced a \$25 prize, and these are a few of the 250 replies I received:

(1) Study cosmic-ray absorption and degradation in the atmosphere, using a bomb high above the earth's atmosphere as an artificial source of cosmic rays. A typical explosion of, say, 10 kt will produce of the order of magnitude of 10^{24} neutrons. Let these neutrons come from a rocket at a height of 200 kilometers. Then at the "surface" of the atmosphere the arrival rate will be 2×10^8 neutrons per cm^2 from this source as compared to order of magnitude figures for the cosmic rays of 10 neutrons per cm^2 per minute. Obviously there is a time factor which is governed by the kind of instruments used and their resolving power, but it is evident that one would have plenty of intensity at hand with which to study neutron absorption to a great depth in the earth's atmosphere. Of course, the results would be relevant only to a small part of the whole problem of cosmic-ray neutrons.

(2) Study the composition of the moon by attaching a device to the tip of a rocket, sending it to the moon, and using it to churn up the moon's surface. Spectroscopic observations would be used to judge the chemical character of the surface.

(3) Many people have proposed to study the properties of the earth by means of seismic waves.

(4) An especially interesting proposal sought to study ionospheric reflection. A nuclear device is exploded high up in the earth's ionosphere. It produces a density of ions which is much higher than the normal ionospheric density. It should reflect radio waves that are not normally reflected. In this way one could hope to communicate by centimeter waves to great distance on the earth. A rough estimate of the figures that enter indicate that to reflect centimeter waves one needs an ion density of the order of magnitude of 3×10^{13} ions per cubic cm. If one cubic meter of material is blown up, vaporized and spread out to a linear extension of the order of one kilometer and provided that too much recombination has not taken place in this cloud of

debris, the number of ions per cm^3 of this material will be diluted to a level of this order of magnitude. Could one expect reflection from a cloud of this linear extension? The major question is sharpness of the ionic density gradient near the surface of the cloud. Turbulence might well make the cloud a diffuse, but still an effective reflector. However, a real worry here is that the refractive index may vary so smoothly at the surface that one does not achieve anything like the normal reflecting power. The proposed experiment might teach much about the behavior of ion clouds.

(5) Many other interesting suggestions were made. The prize winner proposed the use of nuclear devices to develop oil fields. This topic will be much more authoritatively discussed in our sessions here!

I. POWER PRODUCTION

REMARKS ON CONTAINMENT OF NUCLEAR EXPLOSIONS

by

Frederick Reines (LASL)

The first time anyone took seriously the problem of containing a nuclear explosion was in connection with the first test of a nuclear weapon at Trinity¹ in 1945. The problem confronting the experimentalists was how to recover the valuable fissionable material in case of a nuclear dud. After much thought which pointed up the magnitude of the containment problem it was decided to design and build an object capable of holding a few tons of high explosive but to make no attempt to contain even a small nuclear explosion. The result was a massive steel case which weighed several hundred tons and yet, despite its size, would merely be a perturbation to a nuclear explosion with an energy release of 10 to 20 kilotons. At test time confidence in the success of the bomb was so great that the container was not used.

The first consideration of a peaceful application of fission bomb explosions was due to John Wheeler of Princeton who noted the measurements on bomb debris by R. Spence of Los Alamos which showed that the bomb was a fast breeder with a breeding ratio greater than unity.² Thermonuclear bombs drastically reduced the price of neutrons, drawing increased attention to the breeding possibility.³ In addition to breeding, some thought has been given to the question of confining a nuclear or thermonuclear explosion thus making possible the generation of useful power.³ If a sizeable fraction of the explosive energy could be economically derived from thermonuclear reactions the world's available energy sources would be correspondingly increased above that from uranium-thorium alone. That such an explosion can be contained if cost is no object is clear. But can it be done in an economical fashion? Can a container be built which will hold high grade heat and will last more or less indefinitely, as would appear necessary in a power generating station?

¹ Trinity was the code name used for the first full-scale nuclear bomb test which took place in New Mexico in July, 1945.

² A breeder is a nuclear device which produces more fissile material than it consumes.

³ F. Reines, On Containing a Nuclear Explosion, LAMS-1859, Nov. 1954.

There are various ways one can approach the problem of containment. For example, make a large cavity and place a device in the middle of a huge mass of water suspended in the cavity. Take the mass of water equal to the yield in kilotons of TNT. In this way we reduce the problem to one of containing a source of lower grade energy -- high explosive, and so make the problem amenable to experimental study starting with small scale. In all the approaches to containment, as in the above, a medium is introduced to degrade the bomb energy before the container walls are struck by the explosion. Since it is clear that the problem increases in difficulty with the yield of the bomb, it is desirable from this point of view to develop small, efficient bombs which produce most of their energy from thermonuclear reactions.

Recently, Harold Busey⁴ at Los Alamos had an idea how to decrease the volume required to degrade explosive energy and we did a simple experiment which gave some interesting results. First observe that the amount of energy which can be absorbed by water in turning it into steam is about the same as the energy released by a gram of TNT. Now if one could arrange to transform rapidly the explosive energy into thermal energy the volume of water required would be quite small -- a 10-meter radius sphere of water would then contain the energy of a 2-1/2 kiloton explosion. The idea was to hasten the rate of conversion from shock to thermal energy by making the water porous via air bubbles for example. The bubbles were to serve as a sequence of discontinuities which would break up and degrade the shock. The experiment consisted of exploding a gram or so of tetryl with an electric detonator in the middle of one-gallon-capacity tin cans with various fillings. We tried air, water, and a mixture of air and water or froth, varied the charge size and made visual terminal examinations of the can. No attempt was made in these survey experiments to optimize conditions, we were looking for gross effects. So, for example, the air-water froth was not uniform nor was the bubble size optimal.

It is clear that the introduction of froth causes a qualitative improvement in the containment achievable with a given container. The extrapolation of these promising results to the interesting cases of nuclear devices

⁴ H. M. Busey, Containing Nuclear Explosions, K-2-3000, Jan. 1957.

is a complicated affair which deserves detailed theoretical study together with carefully controlled experiments.

The following table summarizes our findings:

Test	Charge (grams)	Can filling	Damage
1	0.59	Water	Seam split
7	0.64	Air	Seam split and holes
8	0.61	Froth	None
6	0.96	Air	Destroyed
9	0.96	Froth	Seam just opened
11	2.5	Froth	Seam split
12	2.5	Air	Can destroyed and shredded

FEASIBILITY AND ECONOMICS OF POWER GENERATION BY NUCLEAR EXPLOSIVES

by

William M. Brobeck (UCRL)

There is enough energy locked in the deuterium in sea water to last the peoples of the earth thousands of years at any imaginable extrapolation of present rates of consumption. This is an encouraging fact for posterity if not for us and it behooves any forward-looking nation to use this to its advantage. A well-supported project is now being carried on with the object of controlling the energy released by the process of atomic fusion. The approach consists of: an attempt to start the reaction on a small scale, to release a small amount of energy steadily and hopefully in order to build up the output, overcoming difficulties, and learning how to handle the process as the power generation increases. Once the controlled release of this energy is demonstrated and an appreciable output is attained, the important matter of costs can be raised and the possibility of competition with other energy sources examined. This program seems eminently reasonable; there is, however, the practical difficulty that after five years of intensive work no energy has been generated and none is now expected for many years.

In this comparatively dismal situation we should perhaps take another look at what we mean by controlled thermonuclear energy. We should not start with a preconceived idea that a thermonuclear power plant must have a machine that looks like one that we might find in an atomic fission or chemically fueled power station. Perhaps we cannot expect to produce a smooth, steady flow of thermonuclear energy, controllable down to zero and used as fast as it is generated. Our picture may have been incorrect. A thermonuclear power plant may be more like a Diesel engine or a hydro plant. It might be run by intermittent explosions as in Otto's famous cycle or involve the sudden lifting of millions of tons of water to flow continuously through hydraulic turbines. These processes are inelegant by present-day advanced engineering standards but they may merit some passing consideration. Such consideration is the purpose of this paper.¹

¹ This subject has also been discussed by F. Reines, LASL, in LAMS-1859.

By the "uncontrolled" release of nuclear energy we mean the release of a great deal of energy in a very short time. The process is not entirely uncontrolled as the time of release can be chosen, but, once started, the reaction must run its course in a few microseconds. The results include the production of a very high temperature and a very high pressure in the form of a shock wave. In the case of the generation of electric power, which is the one we will consider, the energy cannot be used as it is released and so must be stored in some form from which it can be withdrawn as required without excessive storage losses.

Some figures here would give an idea of the possible magnitudes involved. A megaton of energy is defined as 10^{15} calories or 4.18×10^{15} watt-seconds, i. e., about one million megawatt-hours. As heat energy this will evaporate about two million tons of water or as mechanical energy will lift two billion tons one thousand feet.

We must not only store the energy of the explosion but we must make sure that most of it gets into the storage medium. As thermal storage appears more attractive than mechanical, we can consider heating a large amount of water. This can be done, at least in principle, with the water in the form of high pressure steam. The diameter of the fireball can be calculated, and we find that, if enough steam surrounds the explosion to contain the energy with a reasonable rise in temperature and pressure, a very small fraction, less than 0.1%, reaches the edges of the volume. That fraction, although small, is still a large absolute value.

We now come to what seems the most difficult problem of all, that of containing the explosion. If we are to hold the necessary volumes of steam at the pressure required to obtain the heat capacity we need, a metal tank is out of the question. The steel required would cost billions. We must find something other than the tensile strength of metal to hold the pressure. The obvious alternative is an underground or underwater cavity.

A cavern under the ground depends on the compressive strength of rock for its support and is preloaded by the hydrostatic pressure of the rock above it. From elastic theory the tangential compressive stress in the wall of a spherical cavity in an infinite medium under hydrostatic pressure equals two-thirds of the hydrostatic pressure less one-third of the internal pressure. Rock is weak in tension but will stand as much as $20,000 \text{ lb/in}^2$ in compression. Assuming this compressive strength we can

hold 5000 lb/in^2 at a depth of 2000 feet without producing tension in the walls. If we consider the effect of a free surface at the ground level, the stresses appear to be about double those quoted above, so that the depth would have to be increased but would still probably be reasonable.

Real difficulty appears in resisting the shock pressures. Although less than 0.1% of the explosion energy may reach the wall, it arrives in the form of a shock wave, which, on reflection, may increase the momentary pressure to many times its static value. The shock pressure can, however, be decreased indefinitely by increasing the chamber volume per unit of explosive energy. Tricks might also be tried to reduce the destructiveness of the shock wave. The vulnerable part of the cavity is the roof, as the floor can be expected to take anything and still be there. The roof, however, can fall down and the cavity gradually rise until it breaks through the surface. The shock pressure on the roof might be reduced by making the cavity non-spherical — for example, one might use a pear shape with the small end up or an inverted U so that the shock wave would travel parallel to the roof and be reflected only from the sides or the floor. There might be a possibility of filling the cavity with some material that would absorb the shock as the wave passes through. Unfortunately, tin cans, broken bottles, and snow are the only materials so far thought of for the purpose. The durability of the cavity under the shocks of repeated explosions seems to be the major question of feasibility.

The underwater alternative would be a concrete spherical tank using the hydrostatic pressure of the water to keep it in compression. The wall thickness to resist 500 lb/in^2 pressure in a cavity 1000 ft in diameter would be several hundred feet. Building this tank, lowering it into the water, and connecting it to the power station would present formidable difficulties. The underground rock cavern seems much more practical.

Some of the other problems do not seem too difficult. The earthquake shock will be strong in the vicinity of the cavity, but experience with the Rainier Shot indicates that underground megaton explosions will not have to be thousands of miles from inhabited areas. The turbo-electric plant could undoubtedly be designed to resist the strong local shock. Heat loss from the cavity is negligible due to the large size and the low heat conductivity of rock. Leakage of steam through fissures could occur; the hope would be that rock without fissures could be found. Solution in the steam

of silica or other compounds from the rock could be an annoying problem but hardly a crucial one. Plants using steam generated underground are in regular operation today.

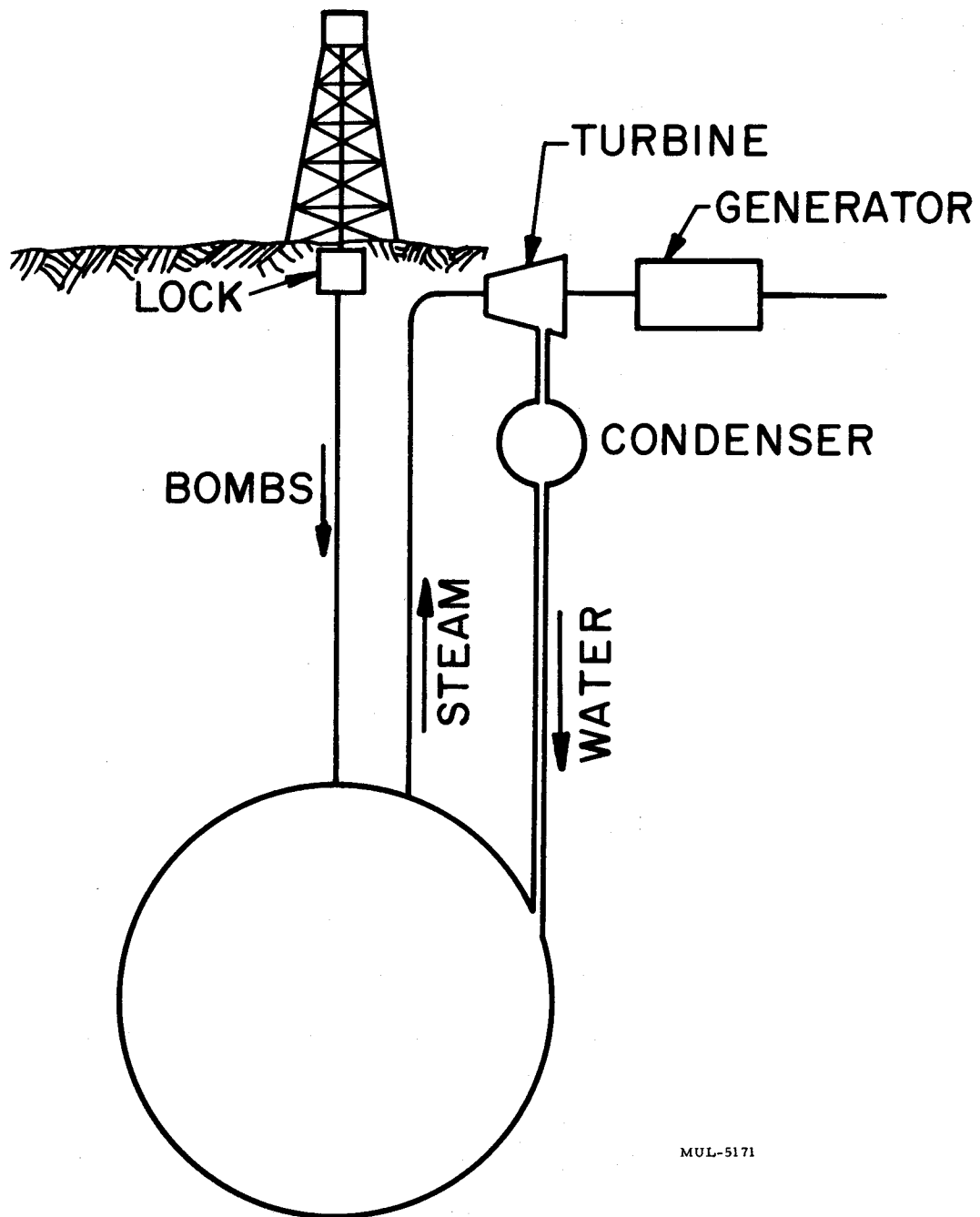
The lower the fission-to-fusion ratio of devices, the better, of course; however, even with fission devices the hazard of a radiation accident is apparently much less than that with a fission reactor, due to the great dilution of the fission products in the steam. It might be possible to remove some of the longest-lived and most objectionable activities by chemical processing, if they appeared in the steam.

It is admittedly presumptuous to discuss the economics of power generation by nuclear explosions, especially since a principle variable, the price of devices, cannot be mentioned.* However, some conclusions might be arrived at, even under the present circumstances. For an economic discussion we need at least a conceptual design. In our case we consider a spherical underground cavity, connected through a steam line to a turbo-generator plant, and a conduit and lock through which bombs could be introduced, as shown in Fig. 1. The cavity volume is taken as 150 cubic yards per ton of explosive, corresponding to a radius of 575 ft and a volume of 30 million cubic yards for 200 kilotons. The plant capability of 2000 megawatts at an assumed thermal efficiency of 25% requires an explosion every 30 hours at full output. The calculated pressures and stresses in the rock wall are shown in Table I. These calculations neglect the effect of the surface.

TABLE I Pressure and Stress Conditions

Cavity volume	: 150 yd ³ /ton of explosive
Steam conditions	
Before explosion	: 2500 psi - 800°F
After explosion	: 3000 psi - 850°F
Hydrostatic pressure in rock	: 3000 psi
Static tangential stress in rock wall	: 4500 psi
Shock pressure at reflection	: 9000 psi
Maximum shear stress in wall	: 4500 psi
Maximum tensile stress in wall	: 0

* The AEC has now released certain cost information. See page 70.



MUL-5171

Fig. 1. Diagram of Conceptual Design of Plant for Generation of Power by Use of Nuclear Explosives.

The cost of rock excavation on the large scale involved here is estimated at \$5 per cubic yard. For the 30-million-yard cavity this represents \$75 per kilowatt, a not unreasonable amount. The cost of the turbo-electric plant would be about \$90 per kw, if provision for the impurities in the steam did not lead to appreciable expense. Assuming annual charges at 15% of these costs and a 70% load factor, these fixed charges would come to 4.0 mills per kilowatt-hour. Operating costs exclusive of fuel should be about one-half mill. If 6 mills, which is the cost of power at the generating plant over a considerable part of the United States, is considered par, there is 1.5 mills per kw-hour or \$440,000 per megaton left for the devices. These figures are summarized in Table II.

TABLE II Power Cost Estimate

Plant capability	:	2000 megawatts
Device yield	:	200 kilotons
Cavity size (575 ft radius)	:	$30 \times 10^6 \text{ yd}^3$
Plant load factor	:	70%
Thermal efficiency	:	25%
Annual charges on investment cost	:	15%
Allowed power cost	:	6.0 mills/kw-hr
Cavity at \$5/cu yd	:	1.8 " "
Turbo-generator at \$90/kw	:	2.2 " "
Operation and maintenance	:	0.5 " "
		<u>4.5</u> " "
Difference allowed for fuel	:	1.5 " "
Balance for nuclear explosive	:	\$88,000

If the process were technically feasible, the ratio of cavity size to device size would appear to determine the economic feasibility. As this ratio is increased the fixed costs would increase in proportion to the fuel costs until the point is reached at which it would be uneconomical even if fuel were free. The ratio is determined by the ability of the cavity to resist the repeated explosions, thus the strength of the cavity is the most important factor to be determined if development of this process were to be undertaken.

The possibility should be mentioned of finding a suitable underground cavern already existing or of forming one by nuclear explosives. These

possibilities do not seem very hopeful, one reason being that such cavities would be in sedimentary rock, which does not appear to have the strength or fluid-tightness required.

In conclusion it can probably be safely stated that generation of power from nuclear explosives is not an entirely absurd idea. As Dr. Herbert York has said about the Sherwood Project, as long as an idea is not impractical by more than one order of magnitude, it merits consideration. This subject appears at least to meet that requirement.

A final, nontechnical comment should also be made. If this process were to become commercially used, thermonuclear devices would be produced in large quantities, and inevitably their design and method of manufacture would be learned by a great many people. This would make it possible for unscrupulous nations or even individuals to build or divert bombs for their own purposes. "Bomb running" could be expected to occur just as does "gun running". This situation which will certainly arise eventually might be considerably hastened by the wide use of nuclear explosives for power generation.

RADIOACTIVITY ASSOCIATED WITH STEAM PROCESSING

by

Roger E. Batzel (UCRL)

Introduction

A serious problem associated with trying to use the steam produced by containment of nuclear and thermonuclear explosions is that of the radioactivity produced as a consequence of the fission yield. The assumption has been made that a 1-Mt gadget having associated with it 30 kt of fission would be detonated every 10 days. The 30 kt of fission is equivalent to about 2×10^8 curies at H + 24 hours which presents a serious problem if the radioactivity appears in the effluent steam.

Consideration must be given to the condensation phase after the device has exploded and the fireball begun to expand and cool. As the fireball temperature decreases to the region of 2000°C to 4000°C, condensation of the vaporized material begins to take place. The major components from which the device was constructed begin to condense as small particles; and then, depending on the partial pressure as a function of temperature for the fission products and other materials, these species begin to condense on and with the major matrix material as the temperature of the fireball decreases.

One of the major uncertainties in the problem is the particle size distribution which actually comes out of the condensation process. Background data are scarce but, typically in air drops where the yield-to-mass ratio is high, particle diameters are in the range of 0.1 to 1 micron. The limited amount of data also indicates that an exponential distribution of the form $N_D = N_0 e^{-D/b}$ (N_D is the number of particles above a given diameter D , N_0 is the total number of particles, b is a constant for a given shot condition) gives a rough fit to observed particle distributions. If the median particle diameter is 0.1 micron, b is 0.14 micron and the fraction of the mass involved in particles with diameter less than 0.1 micron is 2%; ~50% of the mass is associated with diameters less than 0.6 micron; and ~90% with diameters below 1 micron.

The problem is discussed on two bases. One case is that of a lined container where the device material should be relatively undiluted with extraneous materials from the walls. The second case is that of an unlined cavity

where wall materials such as silica and fission products may be expected to be found dissolved in the steam.

Lined Cavity

For the lined-cavity situation, the problems associated with radioactivity in the steam are a sharp function of the settling rates through the steam of the condensed post-explosion particles. If the particles settle out very rapidly to the bottom of the cavity, the steam coming out will be relatively clean. However, if the particles settle slowly, the effluent steam will contain a major fraction of the radioactive debris.

In order to determine what fraction of the particles will remain in the steam, the rate of settling of typical particles can be calculated. Assuming the temperature of the steam to be 1160°F and the pressure to be 3500 psi, the viscosity is 3.3×10^{-4} poise. Using Stokes' law which is applicable for settling and assuming the matrix to have a density of about 5.0 (approximately the density of Fe_3O_4) the following rates of settling were calculated:

<u>Particle diameter</u> <u>(microns)</u>	<u>Settling rate</u> <u>(feet per day)</u>
10	2600
5	650
1	26
0.5	6.5
0.1	0.26

Obviously, if particle size distributions typical of a high yield-to-mass situation occur as a result of the detonation, a major fraction of the radioactivity will be found in the effluent steam. A large fraction of these particles would be expected to deposit in the power generation system and the entire system would become seriously contaminated.

Assuming the volume turnover rate to be about 20% every 10 days and no settling out of material, there would be, at equilibrium, the equivalent of 1 bomb's worth of mass being pumped out of the cavity every 10 days with its equivalent amount of short- and long-lived debris. The problem of trying to remove several hundred pounds per day of heavily contaminated 0.1- to 1-micron particles from about $7 \times 10^7 \text{ ft}^3$ of steam at ~1100°F and 3000 psi

has no easy solution. One possibility exists in the use of electrical precipitators which have efficiencies of ~90% in this particle-size range.

Electrical precipitators have been operated at the required temperatures and at pressures somewhat lower than those required, but there appears to be nothing fundamentally wrong with consideration of an electrical precipitator for this application. Industrial units handle volumes of materials 4 or 5 times those expected in this application.

Unlined Cavity

There is an additional complication for an unlined cavity in that certain materials tend to have a limited solubility in high pressure and high temperature steam. For example, silica is soluble in supercritical steam to the extent of hundreds of parts per million depending on the temperature and pressure of the steam.¹ It has been observed that silica already dissolved in steam tends to dissolve other materials normally only very slightly soluble in steam.

To get an idea of the concentration of materials to be expected, 8000 pounds represents on the order of one part per million of matrix. Without a liner in the cavity, one may be faced with a mass of dissolved material containing the bulk of the fission products which will be pumped out with the steam and appear collected on turbine blades and cooler parts of the external facility.

Again, there is another possible application where there may be a possibility of dissolving, in steam or steam-containing silica or other dissolved compounds, fissionable material produced from a detonation in such an enclosed cavity. Above the critical temperature for steam, the solubility of materials increases as the temperature is lowered and the pressure raised, so it is possible that a fair fraction of the condensing material could be dissolved in steam and recovered in an external system.

Conclusion

If the residual material condenses out as particles and if the particles are large enough, there is no serious problem with the associated radioactivities; if the particles turn out to be small, there is the possibility of

¹ Morey, George W., *Economic Geology*, 52, 225 (1957).

removing the radioactivity with an electrical precipitator. However, if there is no liner and there is silica dissolved in the steam, a fair fraction of the fission products may dissolve in the steam and collect on turbine blades and lower temperature parts of the steam-handling facility. The radioactivity associated with 30 kt of fission ($\sim 2 \times 10^8$ curies at H + 24 hours) represents a very difficult handling problem.

ECONOMICS OF EXCAVATION

by

Marc Peter, Jr. (Rand Corp.)

I was asked to present cost estimates of large excavating operations with particular reference to two structures:

1. A hollow sphere with a radius of 750 ft and its center about 4000 ft below grade.
2. An open cut similar in size to the Panama Canal.

It must be stressed that excavation and mining costs are notoriously sensitive to local conditions and vary widely. Moreover, published records are scarce and accounting methods are by no means uniform. Average costs therefore can only be taken as "ball park" estimates.

The Hollow Sphere

There is no record of underground excavation comparable in size and depth to the specified sphere. The best approach is to assume a typical "open stope" method of work wherein roughly one-third of the original material is left in the form of a honeycomb of pillars and arches which provide the necessary structural support. The honeycomb is then removed concurrently with the installation of a suitable lining.

On the basis of published records (1951-1954) of mining operations of rather small size, average unit costs are estimated as follows:

Open stope excavation	\$ 2.00 per ton
Horizontal transportation within sphere	.25 " "
Vertical hoist transportation to surface	.75 " "
Surface disposal	.30 " "
Total:	\$ 3.30 per ton

Assuming the volume of the sphere to be 60 million cubic yards of 2 tons per yard, the total rough excavation and surface disposal cost is of the order of 400 million dollars. Contingencies, such as water pumping, likely to be met under the specified circumstances, are not included in the estimate.

The cost of the sphere lining can only be estimated on the basis of rather crude assumptions. First, steel is the preferred lining material since the properties of concrete are not suitable to the expected use of the sphere. Heavy steel construction for the specified conditions is estimated

to cost \$500 per ton in place. Second, the external load on the lining is equivalent to about 2000 psi water pressure, irrespective of the arching action of the ground cap. Third, the minimum internal pressure pulse is estimated at 10,000 to 15,000 psi, which is somewhat less than the passive resistance of the ground material at these depths.

However, the effects of repeated shocks and of the thermal pulse on the lining should be taken into account. As a rough approximation, these are assumed to be equal to a static internal pressure of 10,000 psi not counterbalanced by any passive ground resistance.

Assuming maximum steel strength of 50,000 psi and lining thickness equal to $\frac{\text{pressure} \times \text{radius}}{2 \times \text{stress}}$ then the lining thickness varies from 75 ft under the highest internal loads and 15 ft under the external load only. This corresponds to a cost range of 7 to 60 billion dollars for the steel lining alone.

These estimates are based on first approximations and accuracy in terms of specific numbers is doubtful. However, the implication is clear that the costs are expensive.

The Canal

The problem of the cost of a canal comparable in size to Panama or Suez is less difficult than in the case of the sphere since working conditions and contingencies are better known. Moreover, a timely article in the February issue of Fortune magazine provides us with reliable data.

In 1950, the Mahaffey report recommending a new sea-level canal parallel to the existing Panama Canal was filed with Congress. On the basis of accurate surveys, the proposed waterway was estimated to cost 2.5 billion dollars and to require 10 years for completion. The author of the Fortune article, however, believes that the 1957 cost would be more nearly 4.8 billion, or 92 million per mile. Approximately 20% of this cost can be assumed to be spent on finish, equipment, and surface structures, leaving some 75 million dollars per canal mile for excavation work alone.

SURFACE MOTION FROM DEEP NUCLEAR SHOTS

by

David T. Griggs (Rand Corp.)

Pinney¹ has computed the surface motions due to a point source in a semi-infinite elastic medium. His analysis is applicable to a source of finite size, so long as its extent is small compared to its depth of burial. With a little care in defining the nature of the source, it is believed that Pinney's values will yield an estimate of surface motions from deep atomic shots.

It has frequently been said that an explosion is not as efficient as an earthquake in producing earth-quaking. This has been true for all atomic shots except perhaps the deep underwater shot, WIGWAM. It may not be true for deep underground shots. Pinney gives the elastic solution for compressional as well as shear sources, and we shall use this to compare the efficiencies, since an atomic shot is a compressional source, and an earthquake is a shear source.

Consider first the compressional source. In a spherical cavity of radius r_o , in an infinite elastic medium, assume that a step function of pressure ΔP causes an increase in volume of the cavity ΔV . Then

$$\Delta P = \frac{\mu \Delta V}{\pi r_o^3}, \quad (1)$$

where μ = modulus of rigidity. The work done on the surrounding medium is

$$E = \frac{\Delta P \Delta V}{2} = \frac{\mu \Delta V^2}{2 \pi r_o^3}; \quad \Delta V = \frac{\sqrt{2 \pi r_o^3 E}}{\mu}. \quad (2)$$

The horizontal component of surface displacement from a P source is given by Pinney:

$$u_p = \frac{A_{pu} \Delta V \cos \phi}{4 \pi a^2},$$

where A_{pu} is an amplitude coefficient which Pinney has computed for a number of cases. Combining this with Eq. (2),

¹ E. Pinney, Bulletin of Seismological Society of America, 44, 571-596, 1954.

$$u_{p(max)} = \frac{A_{pu} \sqrt{2\pi r_o^3 E/\mu}}{4\pi a^2} = \frac{A_{pu}}{2a^2} \times \sqrt{\frac{r_o^3 E}{2\pi\mu}} \quad (3)$$

Similarly, the vertical component is

$$v_{p(max)} = \frac{A_{pv} \Delta V}{4\pi a^2} \quad .$$

In the case of a shear source, consider a spherical cavity of radius r_o subject to solid body rotation due to a step function of torque T_o .

$$T_o = \frac{4}{3} \tau_o r_o^3 \quad , \quad (4)$$

where τ_o is the maximum shear stress at the boundary of the cavity.

The work done on the medium is

$$E = \frac{2}{9} \frac{\tau_o^2 r_o^3}{\mu} = \frac{T_o^2}{8\mu r_o^3} \quad ,$$

$$\text{or} \quad T_o = \sqrt{8\mu r_o^3 E} \quad . \quad (5)$$

Pinney gives the displacements

$$\text{horizontal: } u_{s(max)} = \frac{A_{su} T_o}{16\pi^2 \mu a^2} = \frac{A_{su}}{4\pi^2 a^2} \sqrt{\frac{r_o^3 E}{2\mu}} \quad (6)$$

$$\text{vertical: } v_{s(max)} = \frac{A_{sv} T_o}{16\pi^2 \mu a^2} \quad .$$

To compare the effectiveness of compressional and shear sources, we take the ratio of the displacements

$$\frac{u_p}{u_s} = 2\pi^{3/2} \frac{A_{pu}}{A_{su}} = 11.3 \frac{A_{pu}}{A_{su}} \quad (7)$$

$$\frac{v_p}{v_s} = 11.3 \frac{A_{pv}}{A_{sv}} \quad .$$

Pinney tabulates values of the amplitude coefficients, A, corresponding to different times, at several values of R/a, where R is the distance from the epicenter and a is the depth of the source. As examples, we shall consider three of Pinney's cases: the closest, farthest, and intermediate. The values are given in the Table III.

TABLE III
Amplitude Coefficients from Pinney.

a. Initial disturbance				b. Rayleigh wave amplitude			
R/a =	0.25	2.00	16.00	R/a =	0.25	2.00	16.00
A _{pu}	0.76	0.73	0.24	A _{pu}	---	---	0.09
A _{pv}	2.91	0.02	0.05	A _{pv}	---	---	0.13
A _{su}	0.03	0.58	0.08	A _{su}	---	---	1.23
A _{sv}	7.84	11.77	-0.45	A _{sv}	---	---	3.72

c. Ratio of P to S amplitude					
		Initial disturbance			Rayleigh wave
		R/a =	0.25	2.00	16.00
11.3	A _{pu} /A _{su}	300.	14.	32	0.80
11.3	A _{pv} /A _{sv}	4.2	0.014	1.3	0.38

From Table III c, it appears that a compressional source produces larger displacements nearby than a shear source of equal energy. The horizontal component of the Rayleigh wave is only slightly less for the compressional than for the shear source at R/a = 16. This ratio should not change much at greater distances.

The fraction of the device energy which goes into elastic waves may be estimated as follows:

$$\Delta PV \approx \frac{E_o}{2}, \quad E_o = \text{device yield}$$

$$E = \frac{\Delta P \Delta V}{2}, \quad E = \text{elastic wave energy}$$

$$\frac{\Delta V}{V} = \frac{3}{4} \frac{\Delta P}{\mu} \quad \text{from Eq. (1)}$$

$$\frac{E}{E_0} \approx \frac{\Delta V}{4V} = \frac{3}{16} \frac{\Delta P}{\mu} \approx \frac{E_0}{10 \mu V} . \quad (8)$$

The volume V to which this relation is applicable is that volume outside which the strain is elastic. Similarly, the pressure P to be used is that of the yield point in compression. The latter typically lies between 1000 and 6000 bars, while μ is about 3×10^5 bars. Accordingly, from 0.1% to 0.5% of the device energy may be expected to be coupled to seismic waves, when the nuclear explosion is in virgin rock.

The seismic energy will be reduced if the device is exploded in a cavity larger than the above volume. Two examples are:

1. 200-kt device in 200-meter-radius cavity:

$$\frac{E}{E_0} \approx 0.01\%$$

2. 1-Mt device in 250-meter-radius cavity:

$$\frac{E}{E_0} \approx 0.02\% .$$

If a 10-Mt device were used to create a hole in a weak, porous rock, the seismic energy would be of the order of 1/4% of the total energy (10^{21} ergs). This corresponds to a magnitude 6.7 earthquake. The seismic energy from subsequent 1-Mt shots in the hole so created would be of the order of 0.00025 of the device yield (10^{19} ergs). This corresponds to a magnitude 5.5 earthquake.

For comparison, the Kern County, California, earthquake of July 1952 had a magnitude 7.5. Its largest aftershock was magnitude 6.2. Extensive damage was produced in Bakersfield, about fifty miles from the epicenter. Damage was caused by aftershocks as well as the earthquake itself, but the extent to which the latter was dependent on prior weakening is not known to the author. The San Francisco earthquake of March 1957 was magnitude 5.5.

The relation between earthquake magnitude and energy is not certain and has recently been revised by a factor 100-1000. The relation used to arrive at the above magnitudes is

$$\text{Log}_{10} E = 9.0 + 1.8 M ,$$

where E = energy in ergs, M = magnitude. Other relations are current, but yield about the same value in this energy range.

The horizontal displacements at varying distances on the surface may be approximated from Pinney's calculations. Equation (3) and Table III yield values appropriate to a homogeneous elastic medium. For "bad ground," Gutenberg² shows that amplitudes can be ten times as great, in the case of Rayleigh waves. Table IV gives values for the indicated assumed conditions.

TABLE IV

Estimated Horizontal Displacements.

A. Assumptions:

10-Mt shot in rock so porous that a 500-meter-diameter hole is created

$r_o = 250$ meters

$\mu = 3 \times 10^{11}$ dynes/cm²

Seismic energy, $E = 10^{21}$ ergs

Depth of burial, $a = 1$ km

Distance from epicenter	Horizontal amplitudes in cm		
R (km)	P wave	Rayleigh wave	"Bad ground"
0.25	3	----	----
2	3	----	----
16	1	0.4	4
160	---	0.04	0.4

B. Assumptions:

1-Mt shot in 500-meter-diameter hole

$r_o = 250$ meters; $\mu = 3 \times 10^{11}$

Seismic energy, $E = 10^{19}$ ergs

Depth of burial, $a = 1$ km

² B. Gutenberg, Trans. Am. Geophys. Union, 37, 759-760 (1956).

TABLE IV (Contd.)

Distance from epicenter	Horizontal amplitudes in cm		
R (km)	P wave	Rayleigh wave	"Bad ground"
0.25	0.3	----	----
2	0.3	----	----
16	0.1	0.04	0.4
160	---	0.004	0.04

The frequency of oscillation of the cavity is given by $\omega = \frac{\sqrt{3}}{2} \frac{V_p}{r_0}$,
 V_p = velocity of P waves. This yields a period of about 1/2 to 1 second for the above cavity. This is apparently about the most damaging frequency for seismic waves.

Conclusion

1. Buried megaton shots may be expected to produce earth-shaking comparable to magnitude 5.5 to 6.5 earthquakes.
2. The fraction of device energy coupled to seismic waves can be reduced by increasing the size of the cavity in which the device is detonated.
3. While the seismic effects of such shots may not be disregarded, measures such as site selection, etc., may reduce the damaging consequences to negligible proportions.

II. OIL AND MINING APPLICATIONS

USES OF THERMONUCLEAR EXPLOSIVES IN THE MINING INDUSTRY

by

C. Richard Adelmann (UCRL)

I would like to divide this application of thermonuclear devices into two parts: surface and subsurface mining. Statistics indicate a natural trend in present day ore reserves: recovery costs are high and rich ore deposits are diminishing. A general look into the future says that the mining industry must turn to the development of the lower-grade ore deposits, but in order to do this, radical changes in mining methods must be made. New concepts must be entertained to economically justify their operation. It seems, therefore, that if the trend is in this direction, then possibly the thermonuclear devices can play an important part in the long-view planning for the maintenance of mineral supplies for, and in, the United States.

Surface Mining

Some of the points which I will touch on as having a potential use for thermonuclear devices are the following:

Mining costs reduction in present-day operations

Economic recovery of low-grade ores

An explosive for mining existing standard and higher grade ores, the economic recovery of which is taxing the ability of present-day explosives

Mining Cost Reduction

If one takes a look at open-pit mining today, one finds that these surface mining operations strip or remove from 5 to 50 tons of waste material to 1 ton of ore mined. Of course, the extreme ratios are dependent upon the value of the ore recovered. However, if one estimates the depth of 50 tons of overburden, it could be as much as 100 ft. It seems very possible that thermonuclear devices could be adapted to a present-day operation to remove this type of overburden.

In looking at the cost of removing waste material, or overburden, the approximate range is from somewhere around 25 cents to \$2.00 a ton. Information available at the present time says that a 100-kt burst placed on the surface will dig a hole conical in shape, 100 ft in depth, with a surface diameter of approximately 600 ft. This amounts to about 500,000 tons of material

removed. Now if we assign 25 cents a ton to this removal, this amounts to approximately \$125,000. By burying a nuclear device at the appropriate depth, approximately ten times the material could be excavated. This will effect a reduction in excavation costs per ton by as much as ten times.

This application seems to be ideal for situations such as the Anaconda-Chile operation in South America where their waste-to-ore ratio is about 10-1, and it is indicated that even a higher ratio of waste to ore is predicted for the future. The population of the area is at a minimum. It is in the desert region of Chile and perhaps an area of this type might be a good area for a test. I am certain that if it were successful, it would have a great influence on the future of the operation.

Another application existed in Canada. The work has been done but an application similar to this has a possible use. The problem at Steeprock was to remove water and mud from a lake. It took many months, I am not sure of the length of time, possibly years of steady pumping to "unwater" and "unmud" the lake. It's conceivable that a thermonuclear device could be designed to undertake a similar project. The Kennecott Mine in Alaska has a possible application. This property throughout the year is covered by sheets of ice. It is a very difficult and expensive mining operation because of the constant task of removing ice and snow.

Development of Economic Recovery of Low-Grade Ores

Mining cost reduction, which I have discussed, is allied very closely to the economic recovery of low-grade ores. The main difference, and the reason why I separated the two, is that I am presuming that once the mining industry had thermonuclear devices for their use, this would perhaps open a new look at what really are low-grade ores. Present open-pit operations, as I have said before, remove economically some 5 to 50 tons of waste material. Perhaps if thermonuclear devices were used, there are many areas in which low-grade deposits are located that could then be opened as new ore reserves.

According to the December 1956 issue of Engineering and Mining Journal, the Southern Peru Copper Corp. in South America is making a major step toward mining one billion tons of low-grade copper ore. Last October they used 145 tons of high explosives to loosen a million tons of waste. It also stated that they have 129 million tons of overburden that must be removed before mining of the deposit is to begin.

Development of Mining Methods Beyond Present-Day Explosives

In the Mesabi Range there is a tremendous reserve of taconite ore. Early, courageous attempts were made to mine this ore. The ore is very hard and it has been said that "If you know how to mine taconite, you can mine anything." This ore reserve contains about 1 to 1-1/2 billion tons, which is equivalent to five hundred million tons of high-grade iron ore. Present day mining and metallurgical methods indicate that this ore supply is good for 50 years. The extreme hardness and abrasiveness has been a challenge to taconite producers from the start. Churn drill holes for blasting could only penetrate 10 to 15 feet per shift. Because of these difficulties, jet-piercing was developed and used with great success. Jet-piercing literally burns a hole into the taconite ore. These holes, by jet-piercing, are drilled at an average rate of 18 to 20 feet per hour, or about 12 times the speed of previous methods, and this solved, at least for the present, the drilling problem. The difficulty now is that present day explosives do not pack the jolt necessary to fragment the ore. Therefore, after the blocks have been broken, it is a tedious and expensive process to reduce the ore material for rock crusher consumption. It seems that this problem could be solved by using nuclear or thermonuclear devices. However, a very close look at this might show a requirement for low yields at low cost.

Another possible use of thermonuclears as a high-explosive replacement is in ordinary open-pit operations. This type of blast would not move the material, but just loosen the deposit and make available a large supply of ore without repetitive drilling and blasting. Something of this nature could be cycled so that the operation would only tie up loading types of equipment to mine the ore, thus reducing the over-all mining costs.

Subsurface

Subsurface application at the present time seems to intrigue few people, probably because the yields just don't fit present need and the unanswered question, "What happens to a thermonuclear device when detonated at subsurface depths?" is a little disturbing. However, one application seems to be outstanding as a candidate for subsurface operations, and that is in leaching processes.

A leaching process is usually done with the ore in place. At the present time, copper is leached from ore-bearing material as a copper sulfate. This is commonly done by allowing the surface waters to percolate down through the ore in place. This is not an efficient method of recovery, but a very inexpensive method. If the ore deposits could be shattered so that the ore-bearing material would have more surface area for water contact, it is possible that the concentration of the solutions could be increased. If this is true, then old depleted leaching areas and new low-grade leaching areas could be used. In looking over this possibility, one is struck by the fact that when a thermonuclear device is placed deep enough to fragment these deposits, the resultant heat generated by the thermonuclear device would create steam in the fissures and fragments of the area. The steam under pressure would then rise up through the deposit, condense and flow back down to the high-temperature region. This would create a recirculation of the ore-bearing solution, and as this works around the periphery of the device area, it is conceivable that the condensate solutions might contain a much higher concentration of the leaching solution. It seems at this time, that an experiment of this kind has a fair justification for further study and if it were successful, it would certainly open a new door for the mining industry.

Dow Chemical Company has released a report on recovery of uranium from the Colorado Plateau ores. This report is a laboratory development of a process for the recovery of uranium from sulfuric acid leaches by solvent extraction. It is realized that this process is of a pilot-type operation, but it is conceivable that this process could be adapted to leaching ores in place and, if so, a thermonuclear application here could also prove worthwhile.

In summing up the mining uses, it seems that the nuclear and thermonuclear devices do have a direct application. The large question is finding the answers to the queries that perhaps will be asked by the mining people:

What yields can you give us?

What contamination can we expect?

What effects do these devices have (rock breakup, surface shocks, etc.)?

When can we plan on using them?

How much do they cost?

And there are no doubt many, many more to be answered.

ON THE POSSIBILITY OF USING NUCLEAR DETONATIONS FOR INCREASING THE YIELD OF OIL WELLS

by

A. T. Biehl and R. R. Henley (Aerojet-General Nucleonics)

Introduction

The purpose of this paper is to examine typical conditions under which a nuclear weapon might be utilized effectively in the profitable recovery of petroleum by increasing the total yield from a given field. In order to accomplish this aim the economics and geology of a typical field, as well as the effectiveness of this and other competing mechanisms under various conditions, are examined.

I. Description of a Typical Field and Well

The typical oil field in the United States might be characterized by the following data:

Density of wells	: 1 per/2-10 acres
Depth of wells	: 4,000 ft (U.S. Av.)
	: 10,000 ft (Louisiana Av.)
	: 8,500 ft (Alabama Av.)
	: 6,000 ft (Texas Av.)
Method of drilling	: Rotary in 87% of cases in 1956
Driving pressure	: 1,000 psi
Diameter of lowest stage of well	: 6 in.
Effective drainage radius (distance from well bore)	: ~650 ft
Porosity	: 20%
Permeability of oil-bearing material	: 100 millidarcys (2-1000 md)
Viscosity	: 2 centipoises
Thickness of oil strata	: 20 ft (can be many strata of 10-20 ft thickness)
% Shrinkage from reservoir to ground level	: 20%
% Recovery	: 20-40%
Approximate production from single 20-ft strata/well	: 700 bbl/day +

Feed	: Gas
Cost	: \$30,000 to 100,000, depending on depth
Price for which crude sells	: \$4.00-4.88/bbl, start of 1957 \$3.00-4.40, 1956

For purposes of this study only gas-fed wells were considered, due to the high probability of ruining a water-fed well by an explosion in the rock below the water layer.

The above description is obviously a vast oversimplification of the structure of many wells, due to the great geological complexities of many of the oil-field areas. Several typical types of geological structures in the vicinity of oil-producing areas are the fault slippage plane, the anticline, the salt dome and the stratified shale-sandstone laminar structures. The areas of perhaps the greatest interest for this examination are the laminar structures, due to their uniformity.

II. Advantages and Difficulties in Using Fewer Wells per Unit Area

Now that the typical well and field have been defined, the question turns to: "Why not space the wells farther apart and save on the high initial investment in the well?" The answer is several-fold.

The effective radius of a well is governed by the production-rate equation:

$$Q = 0.007082 \frac{kh \Delta P}{\mu \beta \ln \frac{R_e}{R_w}},$$

where

- Q = production rate in barrels/day
- k = permeability in millidarcys
- h = height of producing layer in feet
- ΔP = driving pressure = $(P_{at R_e} - P_{at well})$
- R_e = arbitrary radius at which pressure is specified in feet
- R_w = radius of well bore in feet
- μ = viscosity of oil in centipoises
- β = shrinkage factor in %

Thus the effective radius of a given well is controlled by (1) the permeability of the diffusing media, (2) the radius of the well bore, (3) the pressure, and (4) the height of the laminar layer as well as irregularities of the real structure as compared with the idealized model used for calculational purposes. The first two, the radius of the well and the permeability of the media are the two considerations which we will dwell upon further. The third, increasing gas pressure, is one of the standard methods of secondary recovery utilizing former wells as gas-injection spots.

The obvious answer then, to increase production from a given well, is to increase the radius of the well and to find a method of increasing the permeability of the media. Three of the many standard methods for increasing these factors are described below.

A. Enlargement Boring. In this case, the diameter of the well is increased up to as much as 2 to 4 feet by the use of an expandable boring tool which is lowered into the well, expanded, utilized, collapsed, and withdrawn. The cored-out area is usually then filled with a coarse, highly permeable sand to prevent the collapse of the bored area. This technique does increase the well radius but does not materially affect the permeability k which is the most sensitive variable as can be seen from

$$Q = \frac{2\pi kh \Delta P}{\mu \beta \ln \frac{R_e}{R_w}}$$

B. Nitroglycerin Blasting. One of the more widely utilized techniques is the detonation of 5-100 quarts of nitroglycerin creating a 4-7 foot spherical hole which is then treated similarly to the cavity created by enlargement boring.

C. Shape Charges. The more recent usage of shape charges has been in an attempt to increase the permeability of the media over a greater radial distance than previously possible. The technique in this case is to detonate 4 to 8 shape charges which fire out radially from the well, perforating the well casing and extending 20-40 ft out into the diffusing media.

D. Pressurized Sand and Water Method. This technique consists of filling the well casing with a sand-water mixture which is then pressurized to about 1000 psi. This pressure cracks the sandstone or limestone within a 10-20 foot radius from the well center. The sand and water mixture then

flows outward, depositing grains of sand in the cracks, maintaining open cracks after the water is pumped out.

III. Utilization of Special Nuclear Devices

From the standard techniques described above, it can be seen that the logical extension of present techniques would be to a device that increases both the well radius and, more importantly, the average permeability of the media by fracture-generation over a wide area. The explosion of a 1-kt device inside the rock strata directly below the sandstone or limestone oil-bearing layer would create this general effect.

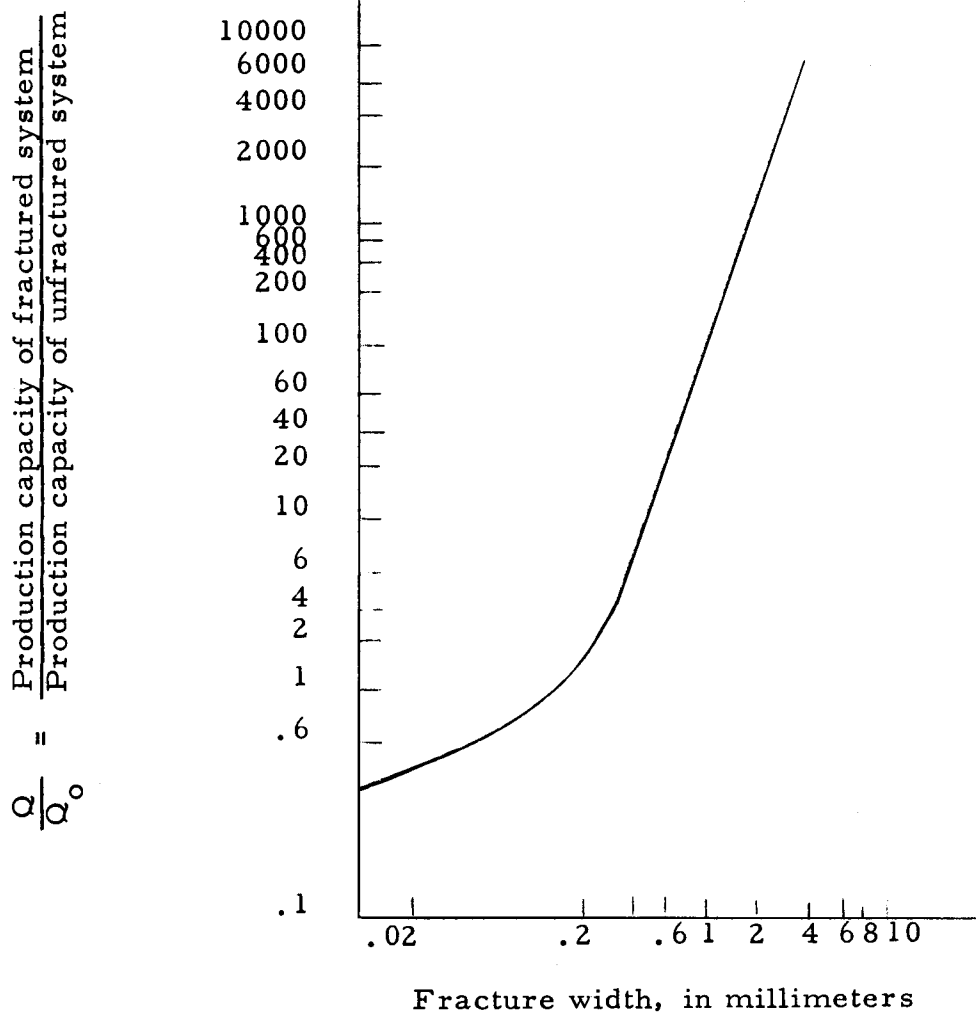
Effects

The explosion of a 1-kt device would create a small fireball of 10-15 feet radius of molten material with fission-product diffusion extending out as much as 50-75 ft. At a distance of 100 meters, the overpressure would be approximately 0.1 kilobars. The probable effect would be to pulverize a radius out to about 100 meters and to extend fissures out a few hundred more meters. (For a detailed description of an underground shot (1.7 kt) see UCRL-5124 on the Rainier underground explosion). In terms of our original well radius of 650 ft, the total area is completely fractured.

The effect of complete fracture of a well area on production is shown below: (From Muskat: Physical Principles of Oil Production)

Extent of fractures	: 300 feet
Initial well radius	: 1/4 foot
Initial limestone permeability	: 10 millidarcys

Since the typical well has a permeability of 100 millidarcys, the fracture width at which the fractures carry most of the oil is a few factors larger. However, the fractures created by the explosion will be of a width several millimeters to several centimeters, thus the difference in permeabilities is insignificant. It can be seen from the following graph that if a nominal fracture width of 10 millimeters is used the ratio of production capacities is more than 10,000/1. These results ignore the possibility of increasing the effective height involved in the radial flow problem. In all probability in a laminated structure, many of the shale partitions between oil-producing layers would be shattered, thus uniting these various production strata. Thus, one can



see the possibility of a large gain in a well from the greatly increased radius of influence of the well and from the large increase in the standard recovery factor of only 20-40%. One must also weigh, however, the possibility of fission-product escape from the lower rock layer into the oil as well as the possibility of ruining the oil pocket in such a fashion as to allow the oil to escape. In considering the net effect, all of these possibilities must be weighed.

Cost

If one arbitrarily assumes that the cost to the customer for the useful energy from a 1-kiloton device is \$500,000, then one well and one device must be the economic equivalent of approximately 10 wells. If the % recovery is increased by a factor of 2 to 3, then one well and a device need replace only

4-5 wells. If it is assumed that the fissures due to the explosion extend out radially only 600 feet and no axial advantage is gained, the new effective radius of the well is 1200 feet. This implies the effective area of a single well is a factor of 4 greater than normal and one well and a device will economically replace 10 wells or considerably more if the fracture distance is more than 600 feet or if strata are axially united. If one assumes only 2 strata are united, the device and one well are a factor of 2 cheaper than the equivalent number of wells.

III. EXCAVATION

EARTH MOVING WITH NUCLEAR EXPLOSIVES

by

Luke J. Vortman (Sandia Corporation)

General

Nuclear explosives promise to open new fields in peacetime earth-excavation projects. Two such uses are explored briefly here, namely, the construction of sediment basins upstream of large dams to prolong storage capacity and the construction of a second canal between North and South America. These studies are based on experimental data from two underground detonations of nuclear devices and on more-or-less uncertain extrapolations from underground high-explosive bursts. The scaled depth of burst used optimizes both crater radius and diameter. Specifically, depth equals $110 W^{1/3}$, where W is yield in kilotons. It is assumed that the crater is a paraboloid of revolution and that the crater dimensions in rock are 80-100% of that expected in earth, an assumption which should be verified experimentally.

Fig. 2 shows the volumes of earth and rock excavated by devices of various yields; Fig. 3 shows the relation between the yield of a nuclear device and the cost of excavating the volume of material represented by that yield by conventional means or of providing an equivalent volume by constructing dams. Examination of the figures shows, for example, that a 100-kt device would excavate 1.2×10^7 cubic yards of earth, thereby providing 7.4×10^3 acre-feet of storage capacity. A dam providing this capacity would cost from $\$9 \times 10^4$ to $\$2.7 \times 10^5$.

To be economical, therefore, thermonuclear excavation would have to cost less than the conventional methods shown in Fig. 3. At present it appears that from a cost viewpoint:

- (1) Devices with yields below 1 kt would not be economical.
- (2) Devices yielding 1 to 10 kt would be economical for rock excavation.
- (3) Devices yielding more than 10 kt would be economical for earth excavation.
- (4) Only devices in the megaton range could compete with dams built by conventional techniques in providing storage capacity.

It should be borne in mind that thermonuclear excavation costs would be increased by shaping. The explosions would create large crater lips with significant amounts of throw-out. Shaping by means of conventional equipment would be necessary but in virtually all cases would cost less than one-fourth the over-all cost.

Radiation Hazard

Radiation from fallout, induced activity, and fission products remaining in the crater constitute both an external and an internal hazard. However, fallout beyond the immediate vicinity of detonation can be minimized by choosing favorable meteorological conditions at the time of firing and by decreasing as far as possible the fission-to-fusion ratio of the device fired. It appears that in the future the ratio can be very substantially reduced. If this proves possible, fallout need not be an insurmountable problem.

Near the detonation point the greatest dangers are induced activity in earth particles and the scavenging of fission products. Since the use of a low fission-to-fusion ratio device is contemplated, the primary hazard would undoubtedly be induced activity. This danger can probably be reduced to virtual insignificance by surrounding the case with materials which will capture or moderate neutrons. Banister of Sandia Corporation, for example, has calculated that by surrounding the case with boron the neutron flux reaching the earth can be reduced to a point where induced activity is no longer an important problem.

As for external gamma radiation, two tolerance levels are reasonable for workers in the crater area. The first is 0.3 r per week, which permits a constant exposure rate of 7.5 mr per hour during a 40-hour working week. The second is 3.9 r per quarter-year, with no more than 5 r in any one year. For workers permitted to receive their full quarterly allowance in a single week, a rate of 97.5 mr per hour would be possible for a 40-hour week. They could not, of course, be exposed for the rest of the quarter. With a device of 1-kt fission yield, the crater would decay to permit the 7.5 mr per hour tolerance rate in about 11 years, and the 97.5 mr per hour rate in about 15 months. For a 40-kt fission yield, the corresponding times would be 30 years and 3.5 years.

It is known from radiation decline in Nevada craters that the decline is much faster than predicted by $t^{-1.2}$ because of weathering. Data from a

1. 25-kt shot show that given levels of radiation are reached at the crater lip in about 0.6 the time predicted by $t^{-1.2}$.

In order to get some idea of the long-range hazard produced by fission products, let us assume that strontium-90 is the primary hazard, that one gram of it is produced per kiloton of fission yield, and that it is all available for solution or suspension in water. Then, it would take 160,000 acre-feet of water per kiloton of yield to keep the radiation level of the water below the maximum permissible for internal consumption.¹ Evidence from air bursts at the Nevada Test Site shows that not only is the amount of biologically available strontium-90 no greater near ground zero than farther out, but even that the ingestion hazard is actually at a peak many miles downwind. Therefore, this hazard will not be as serious near the work areas as around possible sources of water and food at greater distance. As far as inhalation hazard is concerned, animal experiments have shown that it is small away from ground zero. Near the crater, respiration protection can be furnished to workers.

Blast Hazard

It is possible that damage could be done to cities, towns and structures in the vicinity of the detonation by either direct blast or refractions from the ozonosphere. Damage from the latter source occurs at a distance greater than that from direct blast. Since glass store windows are not damaged by peak-to-peak pressures of less than 5 millibars (if simple precautionary measures are taken), overpressures in excess of 5 millibars could be tolerated only at the risk of some damage (broken plate glass windows). Where broken windows (small panes) can be tolerated in small settlements, pressures as high as 17 millibars might be allowed. Fig. 4 shows the maximum distances² at which critical peak-to-peak pressures from refracted blast occur versus weapon yields. Reflections from the ozonosphere occur at greater distances leaving zones of silence in between. The distances at

¹Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water, U.S. Department of Commerce, National Bureau of Standards Handbook 52, March 20, 1953.

²Reed, J.W., Observations and Analysis of Sounds Reflected from the Ozonosphere During Operation REDWING, Project 31.1, WT-1357, Sandia Corporation, to be published.

which the refracted pressures occur, and their magnitude, are a function of the meteorological conditions at the time of the detonations. By a careful choice of meteorological conditions, areas susceptible to blast damage could be placed in a zone of silence. Future microbarographic blast prediction programs should be designed to provide the basic information required for deliberately placing vulnerable areas within a zone of silence.

Use of nuclear devices for peacetime engineering thus appears feasible within the limits of cost outlined earlier, provided that (1) fission-to-fusion ratios have been reduced, (2) due care is taken to minimize ingestion and inhalation hazards, and (3) firing times are chosen for meteorology which adequately minimize remaining dangers from fallout and blast.

Sediment Basins

Discussion

Can a crater from a nuclear device be used economically as a sediment basin to prolong the life of an existing reservoir? Local reservoirs might be used to test the economic feasibility of nuclear devices, although blast and radiation limitations would prevent uses of such devices, for example, in the settled areas of New Mexico where reservoirs are located. Table V presents information from the Corps of Engineers for three New Mexico reservoirs.

TABLE V

Name	Cost	Storage (acre-ft)	Sediment reserve (50 yrs) (acre-ft)	Sediment reserve (% of total)	Sediment reserve (cu yd)	Yield req'd for equivalent crater (Fig. 1)
Jemez	\$4,056,000	120,000	47,000	28	7.6×10^7	640 kt
Two Rivers (Hondo)	6,050,000	207,500	6,000	3	9.6×10^6	80 kt
Los Esteros (Pecos)	7,060,000	587,000	60,000	9	9.7×10^7	800 kt

If sediment estimates are accurate, sediment reserve would be exhausted in fifty years, thereafter depleting the storage capacity of the reservoir. Sedimentation rate is so small for the Two Rivers and Los Esteros reservoirs that it would be 900 and 300 years, respectively, before they were reduced to one-half capacity, and the possible depletion of their capacity can cause little concern.

today. The Jemez reservoir, primarily for sediment control, would have its capacity reduced to one-half in 125 years and have a useful life of only 200 years. After 50 years a 640-kt device would be required to restore its sediment reserve.

Conclusions

Provision for sedimentation reserve made in the design of dams is such that the need for additional sediment capacity occurs not earlier than 50 years after construction and that an additional dam would provide the required reserve more economically than excavation of the required volume. Therefore, it is concluded that a nuclear device would offer no advantage under these circumstances.

If, however, no site were available for an additional dam and if the cost of restoration of sediment capacity were warranted, then additional sediment capacity must be provided by excavation. From Fig. 3 can be determined what the cost of a nuclear device would have to be to excavate a required volume at a cost less than that of excavation by conventional means.

A Second Isthmian Canal

Background

It has been estimated that the capacity of the Panama Canal must be doubled within forty years,³ and that it will be unable to handle the required volume of traffic after 1961.⁴ The Department of Defense has spearheaded the effort either to increase the capacity of the present canal or to find a suitable route for a second canal. A "Third Locks" project was authorized in 1939, stopped in 1942, and not resumed. In 1947 the governor of the Panama Canal Zone reported that the cost of converting the present canal to a sea-level canal would be an estimated \$2,483,000,000,⁵ and would require from 10 to 15 years. At that time an alternate route was examined

³ Spaulding, D. C., "Panama Canal Half Big Enough," Nation's Business, 43:72-77, February 1955.

⁴ Hardy, Rufus, Executive Dept., The Panama Canal. Twenty-fifth Anniversary, The Panama Canal Press, Mount Hope, Canal Zone, 1939.

⁵ The Panama Canal, Encyclopedia Britannica, Vol. 17, p. 171ff, ed. 5, 1956.

(the Chorrera-Lagauto route) which lies west of the present canal just outside the Canal Zone.⁶ In 1948, Army Secretary Kenneth Royal made a study of the Isthmus for possible routes for a sea-level canal in which he gave considerable attention to a route through northern Colombia.⁷

It is the purpose here to examine available routes for a sea-level canal and to determine whether or not nuclear devices could assist in its construction. No consideration has been given to other than a sea-level canal. Whether the present canal should be converted or a new route chosen is a matter of the relative costs of each and the desirability from a military and political standpoint of having routes through more than one country.

The Isthmian Canal Commission,⁸ before the Panama Canal was begun, reviewed several likely routes across the Isthmus.* These are shown in Fig. 5. The most northerly was the Tehuantepec route in the Mexican states of Oaxaco and Vera Cruz (not shown in Fig. 5), which has the advantage of lessening the shipping distance between our east and west coasts by 1200 to 1300 miles. A canal across this route would be 144 miles long across the Tehuantepec summit which is about 700 feet high at Tarifa Pass. A conventional canal would require 20 locks with an average lift of 35 feet. The summit is broad and the route has a relatively uniform slope from the summit to the sea. The amount of excavation which would be required for a sea-level canal is prohibitive and, although it is an economically desirable location for a canal, all studies have found it an impractical route.⁹

The next route south was in Nicaragua (Route 5 in Fig. 5), making use of the San Juan River on the Atlantic side, Lake Nicaragua which empties

* For a comprehensive and interesting account, see The Land Divided: A History of the Panama Canal and Other Isthmian Canal Projects, Gerstle, Mack; A.A. Knopf, 1944, New York.

⁶ "Sea Level Canal, U.S. Engineers Complete Panama Survey," Business Week, p. 94ff, May 3, 1947.

⁷ "Another Ditch?" (Columbia) Time, 52:34, August 16, 1948.

⁸ Report of the Isthmian Canal Commission, 1899-1901, Washington, D.C., Government Printing Office, 1904.

⁹ Shufeldt, R. W., Reports of Explorations and Surveys to Ascertain the Practicability of a Ship Canal Between the Atlantic and Pacific Oceans by Way of the Isthmus of Tehuantepec, Washington, D.C., Government Printing Office, 1872.

into it, and the Rio Grande on the Pacific side, a total length of 183.5 miles. Eight locks would have been required to reach Lake Nicaragua which is 110 ft above sea level. Even if the amount of excavation which would be required for a sea-level canal were not prohibitive, the resulting drainage of Lake Nicaragua would be politically prohibitive.

The next route south of Nicaragua was the Panama route (Route 8 in Fig. 5), the one chosen for the present Canal. Because of the concentration of population and facilities in and around the Canal Zone the use of nuclear devices cannot be considered for that location. It might be pointed out here that the defense of the canal indicates a desirability of having any new route located away from the present Canal.

The 1947 estimate of the sea-level Panama Canal (\$2,483,000,000) would, if construction costs continue to increase as they did prior to 1947, increase to about \$4,500,000,000 by 1960. This latter amount can be used for comparison with the costs of alternate routes, if one keeps in mind that it includes costs of related construction in addition to excavation alone.

The next routes surveyed by the Commission were the Darien routes. The first of these is the one from Mandinga Harbor, Gulf of San Blas via Chepo River to the Bay of Panama (Route 9 in Fig. 5). This route lies between 33 and 63 miles east of the present canal and is 37 miles long. The profile of this route is shown in Fig. 6. The original concept envisioned a sea-level route with a tunnel 4.2 miles long piercing the Carti-Mamoni Divide. The cost of a sea-level San Blas canal was estimated in 1899-1901 to be \$289,770,000. This was 150% of the estimated cost of the existing Canal but only 80% of its final cost. Using procedures to be explained later for other routes, it is estimated that not less than 35 megatons would be required for simultaneous excavation to sea level of that portion of the divide for which the tunnel was planned plus 1-1/2 miles on either side. As can be seen from Fig. 4 and the discussion of other routes, it would be impossible to fire such a large detonation within 50 miles of Panama City and particularly so close to the present Canal.

The Caledonia sea-level routes lie farther east—about 105 miles from the present Canal (Route 10 in Fig. 5). There are three alternate routes, each using separate valleys: the Caledonia, the Aglaseniqua, and the Sassardi (Figs. 7 and 8). The routes are about 54 miles long. The first 17 miles on the Pacific side from San Miguel Bay to the north of the Rio Lara is almost

entirely a dredging operation. The three routes are the same north-eastward to the Rio Chucunaque, thereafter following separate paths. The Commission estimated the cost of the Sassardi, Aglaseniqua, and Caledonia routes at 263, 283, and 320 million dollars, respectively, based on the prevailing costs in 1900. (Compare these with the Commission's estimate of \$195,000,000 for the existing Canal and its final cost of \$366,650,000.)

The cross-section area of the Sassardi route is less than that of the other two routes and less than the cross-section area of the San Blas route. Hence, the Sassardi route appears to be the most feasible of the four Darien routes.

The most southern routes examined lie entirely within what is now the Intendencia del Choco, Colombia (Fig. 5). One route (Route 16 in Fig. 5) lies from the Caribbean and the Darien Gulf south up the Rio Atrato to the confluence with the tributary Rio Napipi, thence up that river, over Limon Pass to Cupica Bay in the Pacific. The Rio Atrato flows more than 135 miles from the Rio Napipi through a low marsh. This could be straightened to a dredged channel 95 miles long whose highest bank at the Rio Napipi confluence is only 40 feet. From this point to the Pacific is about 28 miles over a pass only 2 to 3 miles from the coast. The maximum elevation of the pass is only 615 feet above sea level. The lower 8 miles of the Rio Napipi flows over a porous humus soil which could probably be dredged leaving little more than 20 miles of dry excavation. The Cupica route appears to be a second route for which nuclear devices are likely to be feasible.

The second Rio Atrato route (Route 15 in Fig. 5) departs at the Rio Truando confluence, leaves the Rio Truando at 95 miles from the mouth of the Rio Atrato, crosses a pass between 850 and 930 feet high at 99 miles, and reaches the Pacific at 105 miles, in Humboldt Bay. By dredging a straight waterway along the Rio Atrato, the total length of the route could be reduced to 95 miles.

Comparison and Evaluation of the Sassardi and Rio Atrato Routes

The shape of the crater made by a nuclear explosion is such that when the necessary depth is acquired for cuts through earth whose surface is 200 feet above sea level the average crater width is more than sufficient for a canal. The slopes of the crater are much less than the slopes of cuts ordinarily made for canals through rock or hard earth and the volume of material

excavated per unit length is so much greater than by ordinary methods that the volume of material is not a satisfactory means of comparison. Estimated costs furnish the best means of comparison.

The present Panama Canal has a bottom width of 500 feet, with the exception of Culebra cut where the bottom width is only 300 feet. The latter may be considered the minimum for ships which can be accommodated by the 110-foot locks. Vessels of the Forrestal class (beam 248 feet) should be accommodated by any new canal, indicating 500 feet as the minimum width. It is desirable that some allowance be made for increase in ship size over the life of the canal. Since the present width of the Suez Canal is 400 feet the proposed 500-foot width would seem reasonable. For the comparisons made herein, a minimum canal depth of 50 feet has been assumed. Throughout the discussion no allowance has been made for underwater shelves, beaching areas, or ship turnouts.

Comparison of Nuclear with Conventional Excavation.

It has been assumed for the costs estimated here that dredging could be used to a point where the grade was 40 feet above sea level, that conventional excavation would be used where the grade was between 40 and 200 feet above sea level, and that nuclear devices would be used where the grade was above 200 feet. It is to be expected that as the cost of devices is decreased, the depth of excavation to which they can be economically applied will be less and even greater savings than those shown here would accrue.

For the comparisons made here trapezoidal cross sections, standard for canal construction, have been adopted. The adopted side slopes are:

Hard Rock	4 on 1
Soft Rock	2 on 1
Earth	1 on 1
Dredging	1 on 2

Since no information on underground conditions of the routes is available, the distribution of earth and rock is unknown; an average slope of 1.5 on 1* has been assumed where the ground surface is higher than 40 feet above sea level and 1 on 2 where it is below 40 feet. No accurate profile is available

* The average slope of 1.5 on 1 does not appear unrealistic in view of the trouble and expense experienced in Culebra cut where 4 on 1 proved unsatisfactory.

for either the Truando or Cupica routes. However, estimates (Fig. 9) have been made from topographic maps which give a profile whose cross-section area is probably accurate within $\pm 10\%$.

Table VI shows the costs of excavation only for each of the three routes being considered. The table also gives the amount of excavation accomplished with nuclear devices and its cost by conventional methods. Estimates of the cost of dredging varied from \$0.35 to \$0.50 per cubic yard, furnished by a Los Angeles engineering firm, to an estimate of \$0.12 to \$0.15, furnished by the Mississippi River Commission, CE, U.S. Army. For the calculations herein an approximate average of \$0.25 has been used.

Comparison of Excavation of the Three Routes by Nuclear Devices

Fig. 10 shows a lateral cross section of the proposed canal with the cross section of the crater resulting from the detonation of a nuclear device of suitable yield. The crater is purposely made deeper than the bottom of the canal so that the crater bottom can contain the material remaining between craters of a series. Also, the throw-out from adjacent craters will leave the apparent crater shallower than that from an individual detonation by an amount which can only be estimated.

Fig. 11 shows the longitudinal cross section through the canal and a series of craters. Spacing the craters used here was such as to equalize the amount of material to be excavated between craters. Table VII summarizes the requirements necessary to excavate a stated length of each route using nuclear devices.

Blast Hazard

The maximum and minimum blast hazard for each site is shown in Figs. 12 and 13. It should be remembered that the maximum distances are distances beyond which overpressures has never been observed. Through a careful choice of meteorological conditions these distances can be significantly reduced -- to $1/3$ to $1/4$ of the maximum distances.* Indian villages, ranches, and settlements are of adobe plaster or thatch over woven bamboo or wood frame. Structures of this type are resilient and not easily damaged by low pressure blast waves.

* Minimum distances might be even less since the values from Fig. 4 are for above-ground bursts while the bursts considered here are those at a scaled depth of 110 feet.

TABLE VI Costs and Volume of Excavation for Three Routes: Conventional Methods

Slope	Sassardi		Rio Truando		Cupica	
	1 on 2	1.5 on 1	1 on 2	1.5 on 1	1 on 2	1.5 on 1
Height above sea level	<40'	>40'	<40'	>40'	<40'	>40'
Length (mi)	24.8	27.6	61	33	91	29.5
Cuts (length [mi] and volume [cubic yards])	24.8, 25x10 ⁶	1.66, 20x10 ⁶ 1.54, 40x10 ⁶ 2.96, 45x10 ⁶ 4.97, 100x10 ⁶ 5.91, 100x10 ⁶ 3.08, 80x10 ⁶ 2.07, 80x10 ⁶ 1.04, 155x10 ⁶ 0.42, 90x10 ⁶ 0.53, 40x10 ⁶ 0.83, 30x10 ⁶ 0.59, 20x10 ⁶ 0.31, 20x10 ⁶ 0.10, 5x10 ⁶ 0.78, 20x10 ⁶ 0.83, 10x10 ⁶	61, 540x10 ⁶	22, 450x10 ⁶ 2.56, 110x10 ⁶ 0.14, 10x10 ⁶ 0.7, 120x10 ⁶ 0.7, 120x10 ⁶ 1.1, 100x10 ⁶ 2.3, 80x10 ⁶ 3.5, 40x10 ⁶	91, 800x10 ⁶	20.2, 400x10 ⁶ 5.6, 240x10 ⁶ 26.5, 230x10 ⁶ 1.0, 50x10 ⁶
Total length and volume	27.62, 855x10 ⁶					
Unit cost per cubic yard (\$)	0.25	4.25	0.25	4.25	0.25	4.25
Cost of total volume if excavated by conventional methods (\$)	6x10 ⁶	3634x10 ⁶	135x10 ⁶	4378x10 ⁶	200x10 ⁶	3910x10 ⁶
Total cost of excavation (\$)	3640x10 ⁶		4513x10 ⁶		4110x10 ⁶	
Portion which could be excavated by explosive (length and volume)	5.73, 440x10 ⁶		6.5, 515x10 ⁶		7.8, 465x10 ⁶	
Unit cost (\$)	4.25		4.25		4.25	
Total cost of excavation by conventional methods (\$)	1870x10 ⁶		2189x10 ⁶		1976x10 ⁶	

TABLE VII Requirements for Nuclear Excavation of Sassari, Truando, and Cupica Routes

Sassari		Truando		Cupica	
Length (mi)	5.73	6.5	7.8		
Number of Nuclear Devices Required	21	27	31		
Approximate Yields (kt) and cost in dollars (Fig. 17)					
1 5500	1×10^6	1 3000	1×10^6	1 1500	1×10^6
2 2500	2×10^6	2 1350	2×10^6	2 1350	2×10^6
1 900	1×10^6	2 2500	2×10^6	2 900	2×10^6
1 500	1×10^6	1 1000	1×10^6	3 600	3×10^6
3 350	2.7×10^6	1 600	1×10^6	2 500	2×10^6
13 250	11.7×10^6	13 350	11.7×10^6	13 350	11.7×10^6
		7 250	6.3×10^6	8 250	7.2×10^6
Total Yield (Mt)	16.200	18.6	15.35		
Cost of Devices (\$)	19.4×10^6	25.4×10^6	28.9×10^6		
Cost of Placing (\$)	1.00×10^6	1.4×10^6	1.6×10^6		
Cost of Finish Grade (\$4.00/cu yd)	27.4×10^6 cu yd 110×10^6	34.9×10^6 cu yd 140×10^6	39.8×10^6 cu yd 160×10^6		
Total (\$)	130×10^6	166×10^6	191×10^6		
Cost of Same Excavation by Conventional Methods (\$)	1870×10^6	2189×10^6	1976×10^6		
Saving (\$)	1740×10^6	2023×10^6	1785×10^6		
Per Cent of Total Excavation Cost	48	45	43		

Assuming that the populations of each Department, State, or Intendencia are uniformly distributed, the number of persons included in a radial distance from ground zero is shown in Fig. 14 for each of the three routes. For example, the minimum distance for a 17-millibar pressure from the Truando route would encompass no people in the Department of Antioquia, 10,000 in the Republic of Panama, and 50,000 in both the Republic of Panama and the Intendencia del Choco. The right margins of the figure indicate the distance to centers of population. The minimum extent of the blast hazard is also shown in the figures.

Blast effects are the major factor likely to limit the yield of a single simultaneous detonation at any one of the three locations. If local conditions were found to preclude a simultaneous detonation of the size shown in Table VI smaller detonations could be used but with certain disadvantages. Some linear overlap would be necessary to prevent throw-out from one detonation filling the crater of an adjacent earlier detonation. This overlap would obviously increase the number of devices to be used as well as increase the total yield.

Fallout Hazard

Infinity dose of fallout radiation from simultaneous detonation at each location is shown in Fig. 15. It has been assumed that the detonation consists of the number of devices given in Table VI and that each has a 40-kt fission yield. The fallout is plotted for a surface burst, since the effect of a deep subsurface burst on fallout has not been determined.

Fallout from the Sassardi location has been plotted for a 10-knot wind with the extent of the 10-r infinity dose contour for a 20-knot wind falling just short of Jamaica. Thirty-knot winds have been illustrated for the Truando site and 10 knots for the Cupica. With a 30-knot wind the 10-r infinity dose falls just short of the Galapagos Islands. A 30-knot wind has the advantage of reducing the upwind extent of fallout and the resulting hazard in areas to be reoccupied after the detonation. Figure 16 based on 5 years of wind data from Albrook Field, Canal Zone, shows the probability occurrence of fallout on a percentage basis as indicated during the first twelve hours of transport of nuclear debris. The desired direction for either the Truando or Cupica routes falls along the line of maximum probability during winter and spring. Even then, the probability of getting velocities as high as 30

knots is extremely low. The probability of getting the desired direction from the Sassardi location is low in all seasons but particularly low in summer.

Table VIII summarizes information on the three routes.

TABLE VIII Summary

	<u>Sassardi</u>	<u>Rio Truando</u>	<u>Cupica</u>
1. Location	Panama	Intendencia del Choco, Colombia	Intendencia del Choco, Colombia
2. Total Length	52.4 miles	94 miles	120.5 miles
3. Dredged Length	24.8 miles	61 miles	91 miles
4. Excavated Length	27.6 miles	33 miles	29.5 miles
5. Length to be Excavated by Nuclear Explosion	5.7 miles	6.5 miles	7.8 miles
6. Dredged Volume	$25 \times 10^6 \text{ yd}^3$	$540 \times 10^6 \text{ yd}^3$	$800 \times 10^6 \text{ yd}^3$
7. Excavated Volume	$855 \times 10^6 \text{ yd}^3$	$1030 \times 10^6 \text{ yd}^3$	$920 \times 10^6 \text{ yd}^3$
8. Total Volume	$880 \times 10^6 \text{ yd}^3$	$1570 \times 10^6 \text{ yd}^3$	$1720 \times 10^6 \text{ yd}^3$
9. Amount of Excavated Volume to be Done by Nuclear Explosion	$440 \times 10^6 \text{ yd}^3$	$515 \times 10^6 \text{ yd}^3$	$465 \times 10^6 \text{ yd}^3$
10. Cost of Total Volume (8)	$\$ 3.64 \times 10^9$	$\$ 4.5 \times 10^9$	$\$ 4.1 \times 10^9$
11. Cost of Dredged Vol (6)	$\$ 6 \times 10^6$	$\$ 135 \times 10^6$	$\$ 200 \times 10^6$
12. Cost of Excav. Vol (7)	$\$ 3.6 \times 10^9$	$\$ 4.4 \times 10^9$	$\$ 3.9 \times 10^9$
13. Cost of Planned Nuclear Excavation (9) if Done by Conventional Methods	$\$ 1.9 \times 10^9$	$\$ 2.2 \times 10^9$	$\$ 2.0 \times 10^9$
14. Number of Units Required	21	27	31
15. Yield Range (kt)	250-5500	250-3000	250-1500
16. Total Yield (Mt)	16.2	18.6	15.35
17. Cost of Devices	$\$ 19 \times 10^6$	$\$ 25 \times 10^6$	$\$ 29 \times 10^6$
18. Cost of Placing	$\$ 1 \times 10^6$	$\$ 1.4 \times 10^6$	$\$ 1.6 \times 10^6$
19. Cost of Finish Grade	$\$ 110 \times 10^6$	$\$ 140 \times 10^6$	$\$ 160 \times 10^6$
20. Total Cost	$\$ 130 \times 10^6$	$\$ 166 \times 10^6$	$\$ 191 \times 10^6$
21. Saving (13 minus 20)	$\$ 1.74 \times 10^9$	$\$ 2.0 \times 10^9$	$\$ 1.8 \times 10^9$
22. Blast (Max. Dist 17 mb)	130 miles	125 miles	120 miles
23. (5 mb)	305 miles	295 miles	290 miles
24. (3 mb)	410 miles	395 miles	390 miles

(Continued)

TABLE VIII Summary (Continued)

	<u>Sassardi</u>	<u>Rio Truando</u>	<u>Cupica</u>
25. Blast (min. Dist 17 mb)	43 miles	42 miles	40 miles
26. (5 mb)	102 miles	98 miles	97 miles
27. (3 mb)	137 miles	132 miles	130 miles
Fallout (40 kt each) for the devices listed in 14 above.			
28. Fallout Sector	90°	70°	70°
29. In Path of Fallout	Jamaica	Galapagos Is.	Galapagos Is.
30. Distance	600 miles	960 miles	950 miles
31. Max. Permissible Wind Velocity	20 knots	30 knots	30 knots

Conclusions

Use of nuclear devices would reduce the cost of construction of an Isthmian Canal over any of the three routes. Radiation from fission products and neutron-induced radiation can be reduced to a point where hazard to workers can be overcome by use of conventional protection measures. The three sites are so located that all downwind fallout could be over open water. Land areas surrounding each of the three sites are sparsely populated and devoid of significant centers of population, easing the problem of evacuation from the sites. Blast hazard might necessitate replacing a single large yield shot with two or more smaller yield shots.

The technical obstacles surrounding the use of nuclear explosives to aid in the construction of a second Isthmian Canal are less formidable than the political obstacles likely to be encountered.

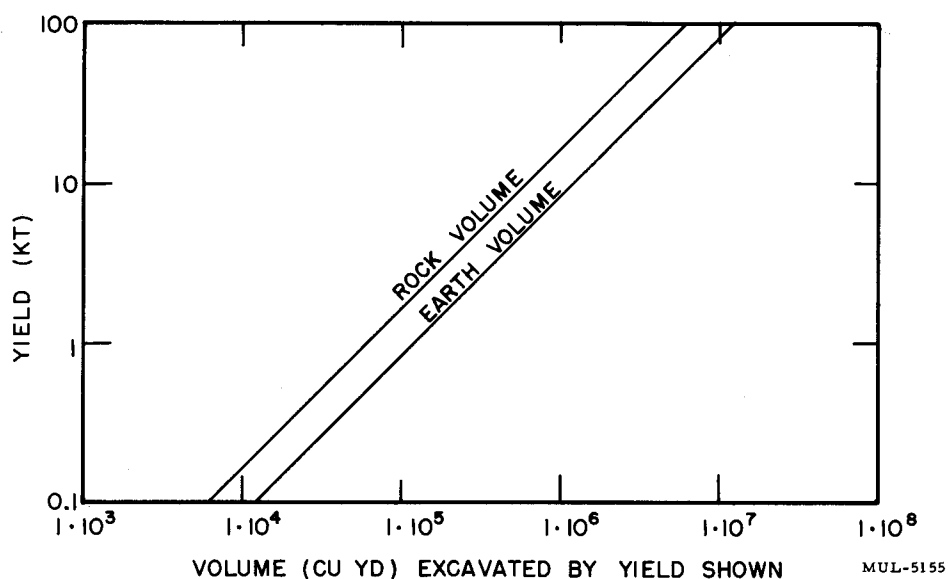


Fig. 2. Volume of Earth and Rock Excavated by Nuclear Explosions of 0.1- to 100-kt Yield.

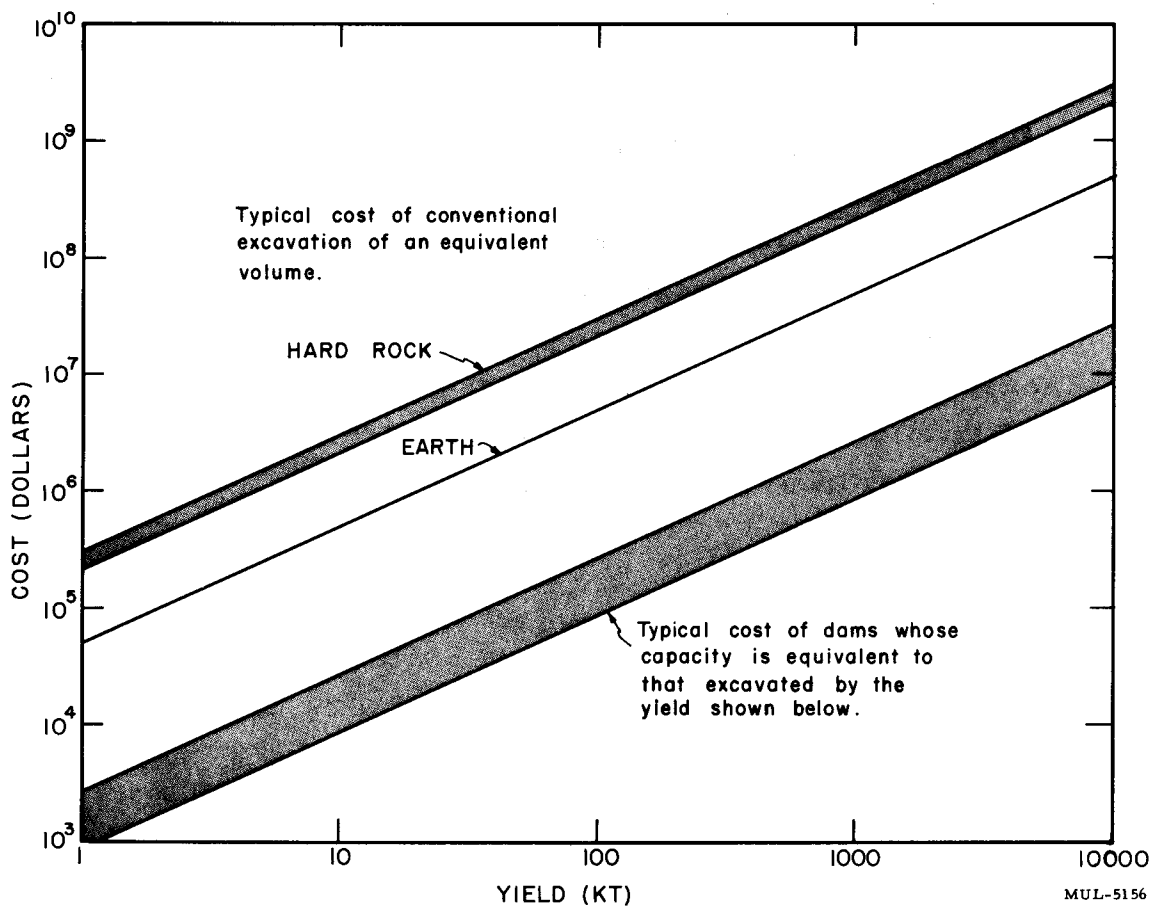


Fig. 3. Typical Cost of Conventional Excavation of a Volume Equivalent to That Excavated by Nuclear Devices of Various Yields.

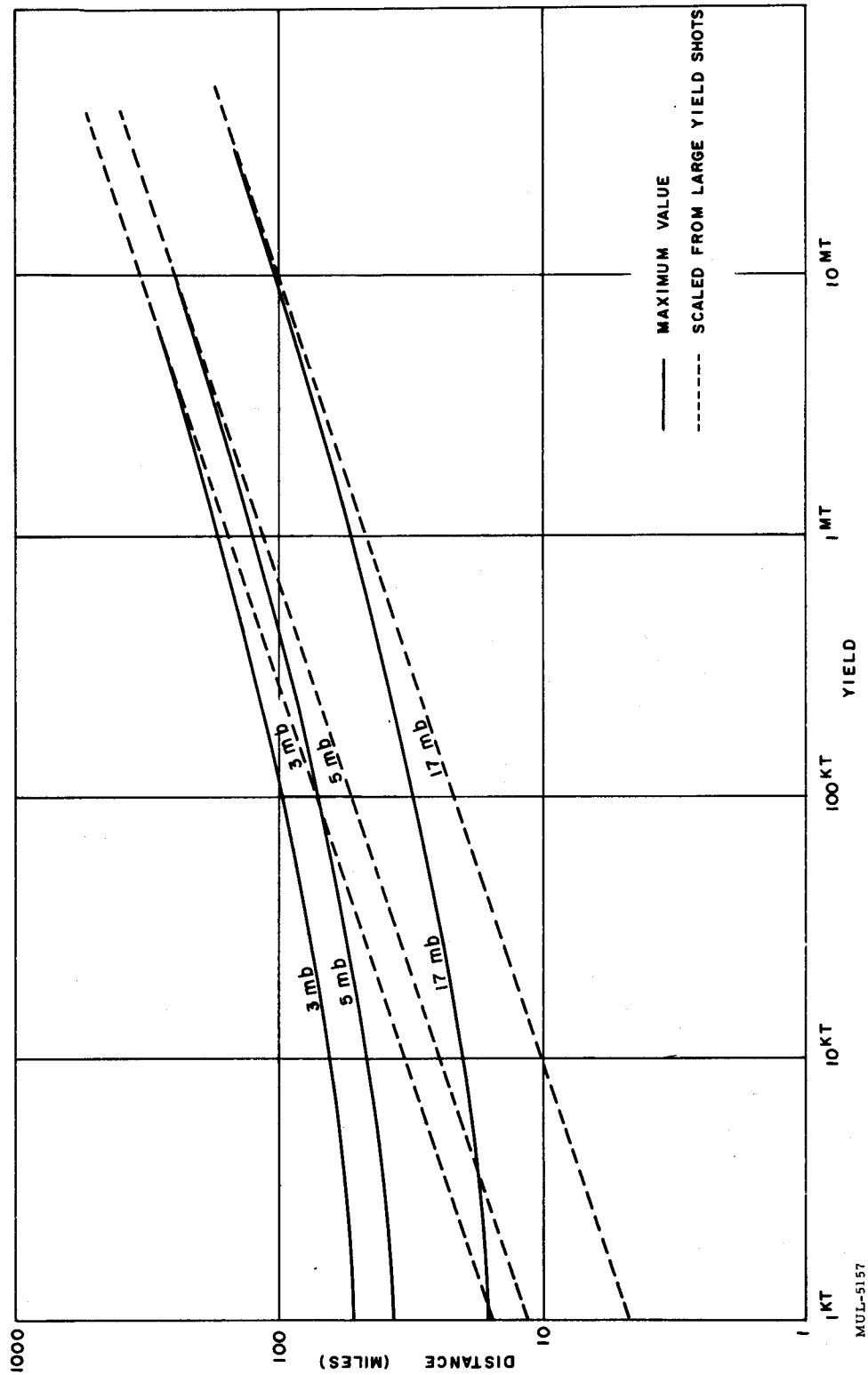


Fig. 4. Distance from Various Yields Burst above Ground to Which Certain Maximum Pressures Would Reach.

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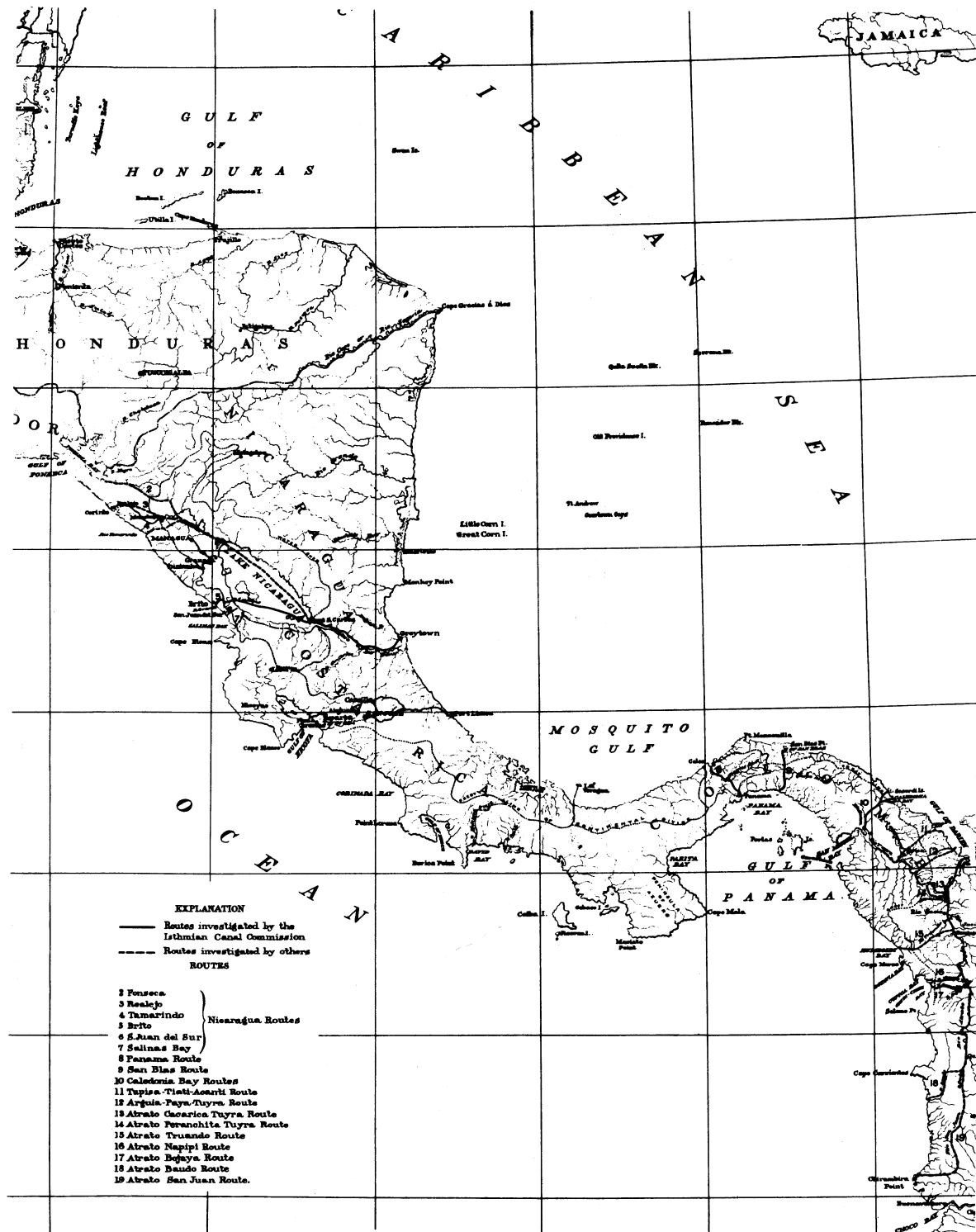


Fig. 5. Proposed Isthmian Canal Routes.

(Reference 8)

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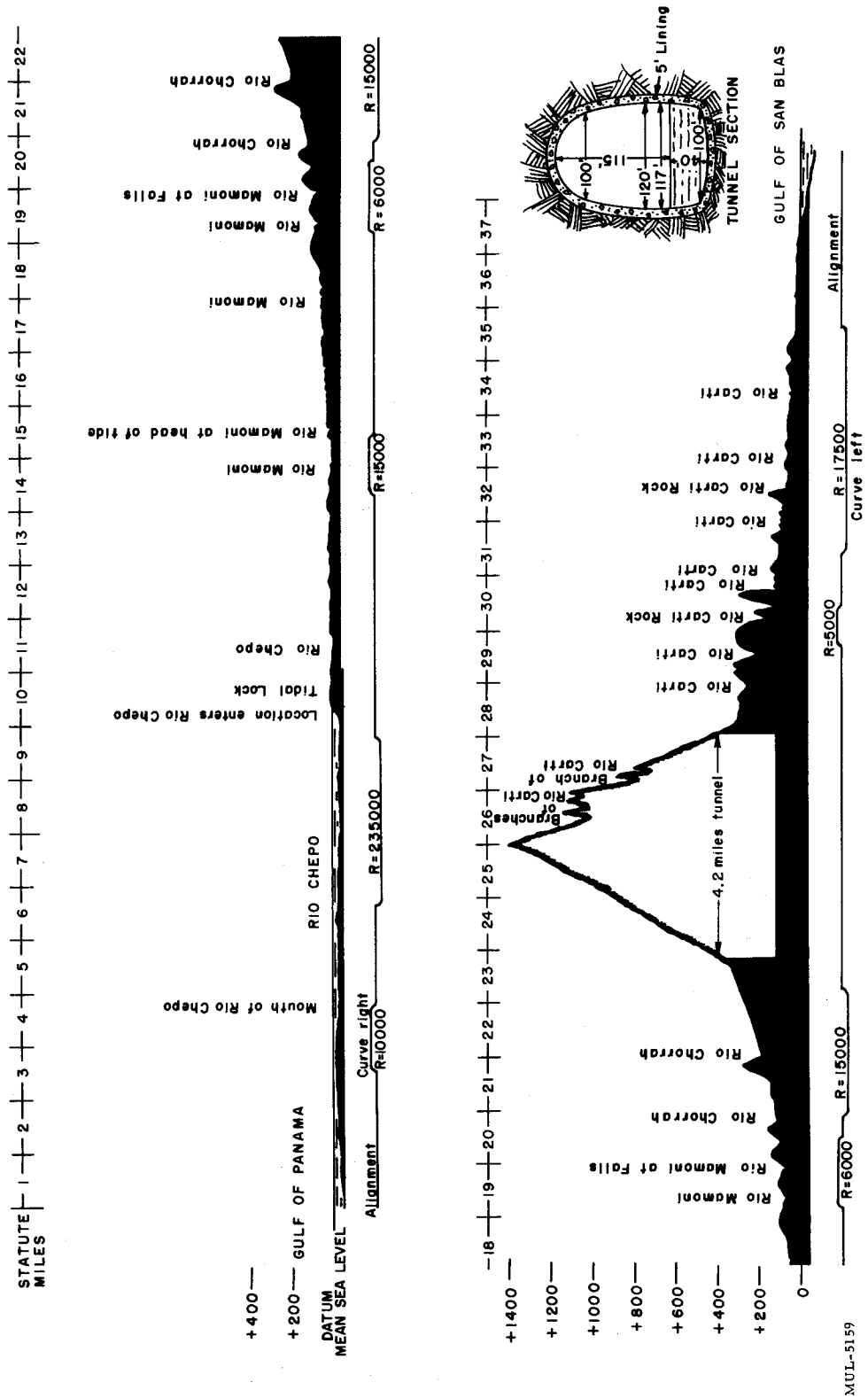
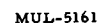


Fig. 6. Profile of Proposed Route: Mandinga Harbor, Gulf of San Blas via Chepo River to Bay of Panama.

(Reference 8)



(Reference 8)

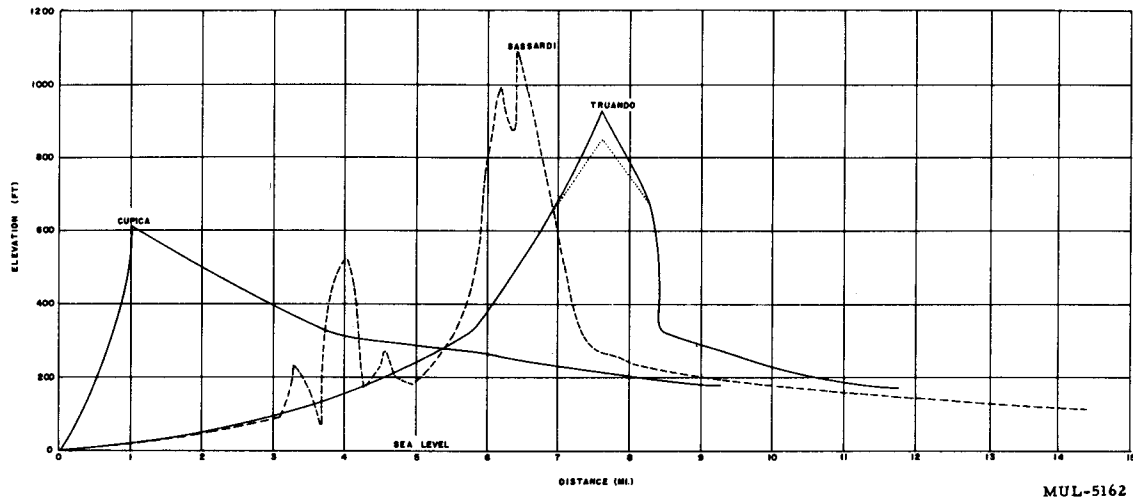


Fig. 9. Estimated Profiles for Sassari, Truando and Cupica Routes.

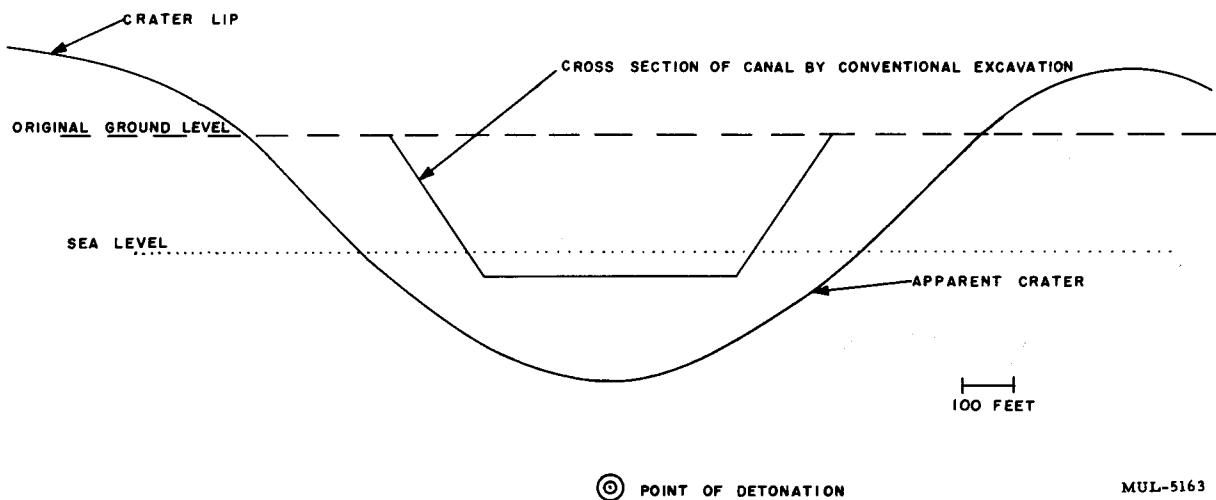
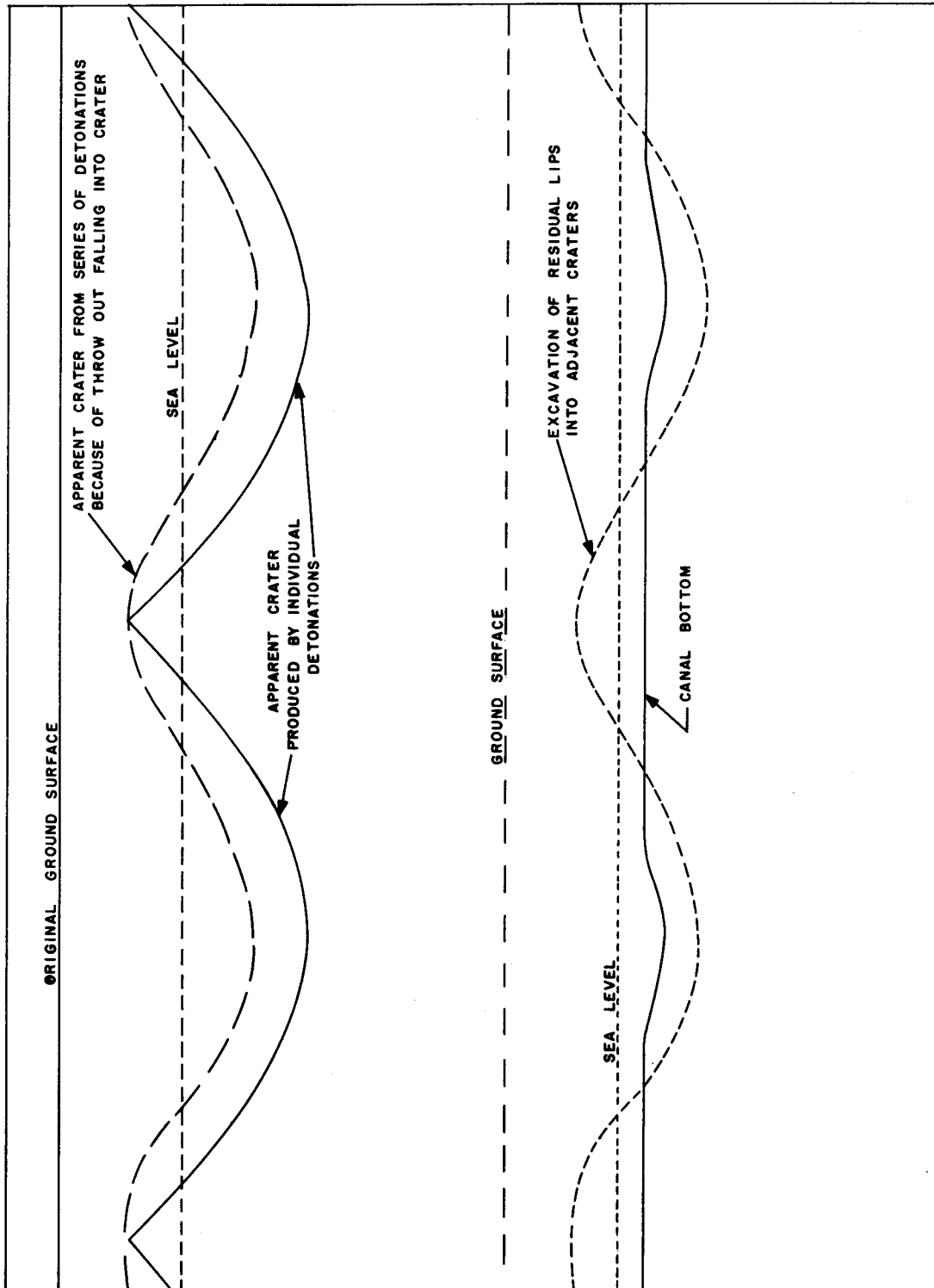


Fig. 10. Lateral Cross Section of Proposed Canal: Conventional Excavation and Nuclear Excavation.



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Fig.11. Longitudinal Cross Section of Canal and a Series of Nuclear-Explosion Craters.

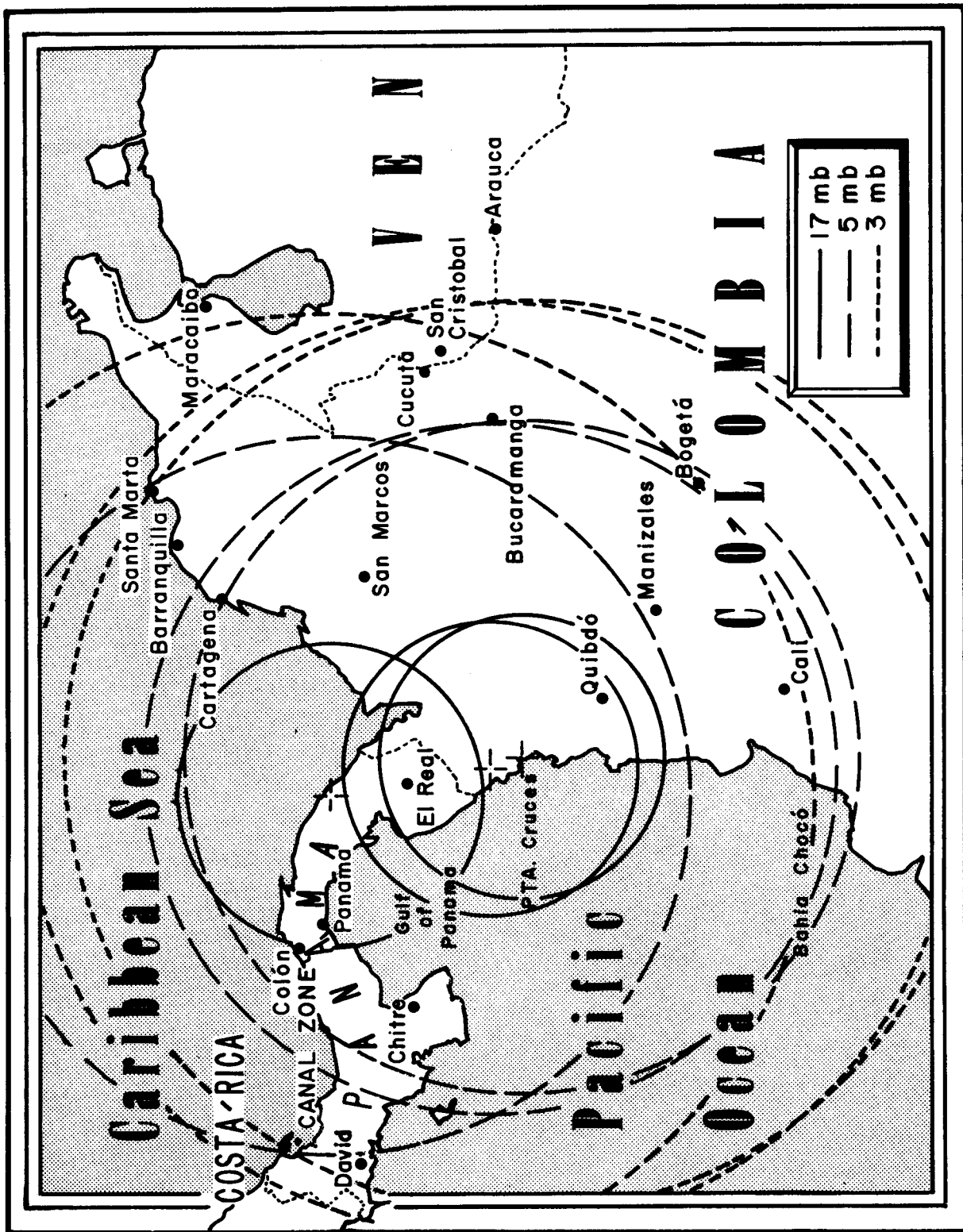


Fig.12. Maximum Blast Hazard for Sassardi, Truando, and Cupica Routes.

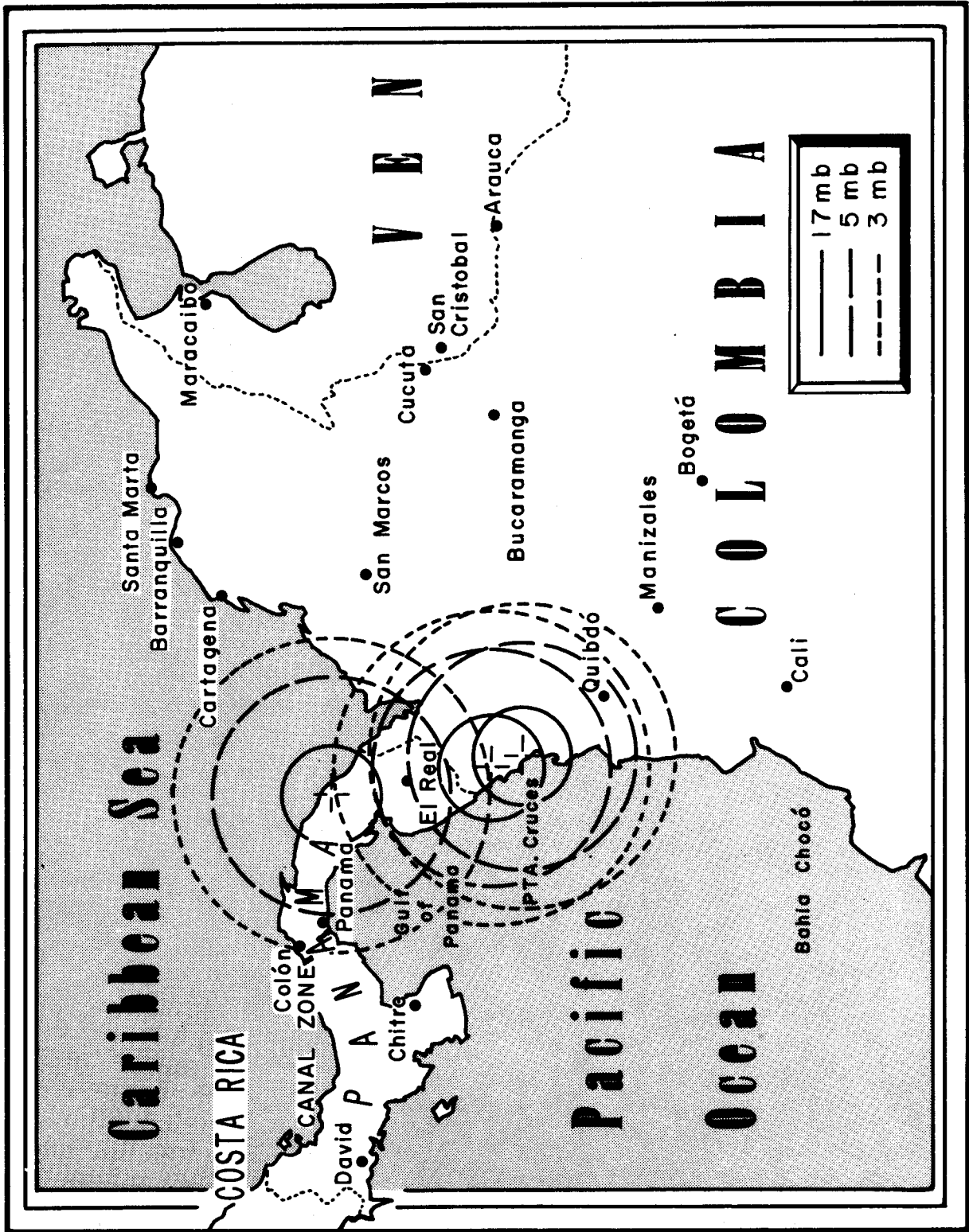
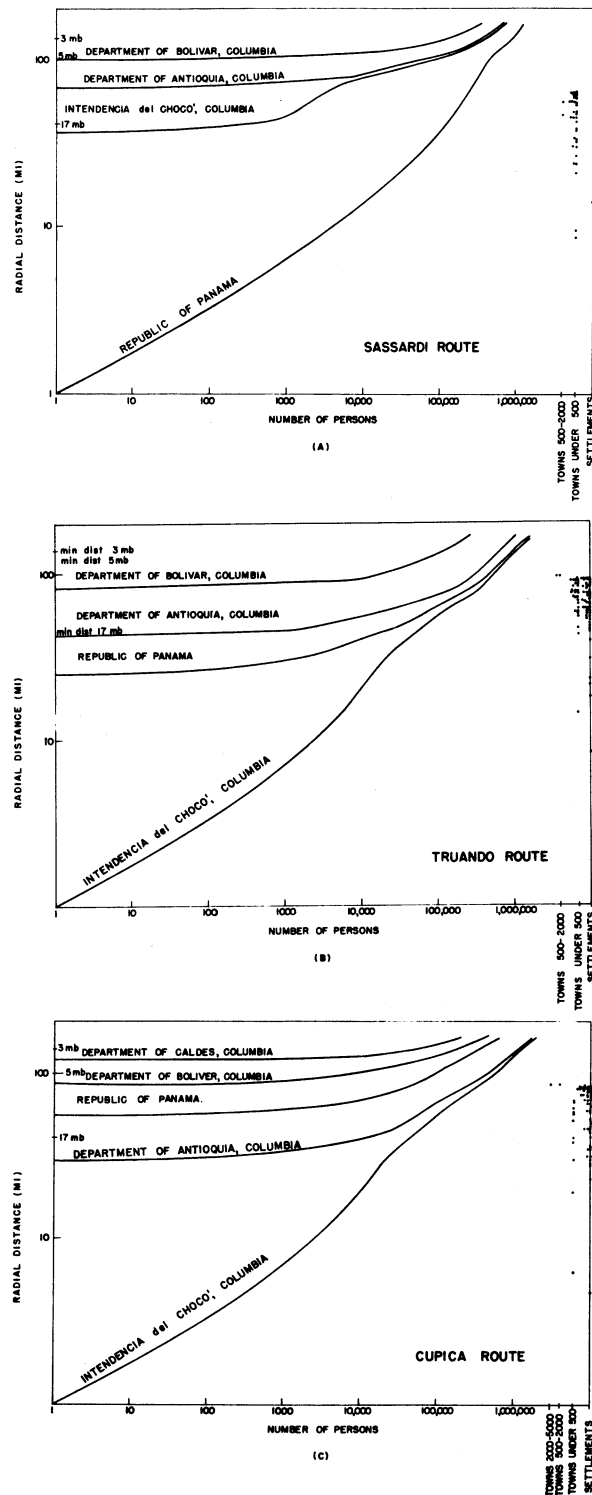
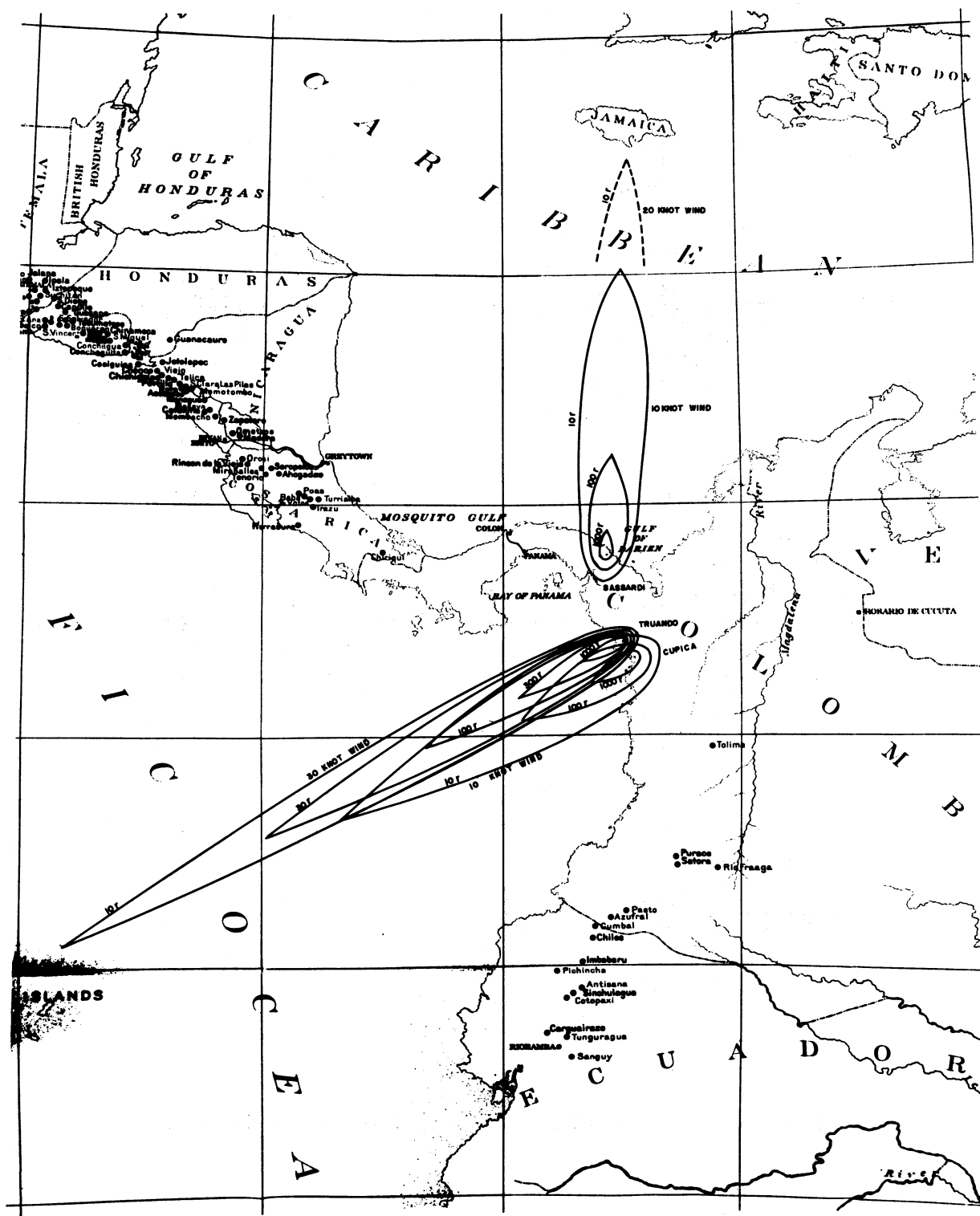


Fig.13. Minimum Blast Hazard for Sassardi, Truando, and Cupica Routes.



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Fig.14. Number of Persons vs Radial Distance from Ground Zero for Sassardi, Truando, and Cupica Routes.



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Fig.15. Fallout Radiation Infinity Dose for Simultaneous Detonations (40-kt Fission per Device).

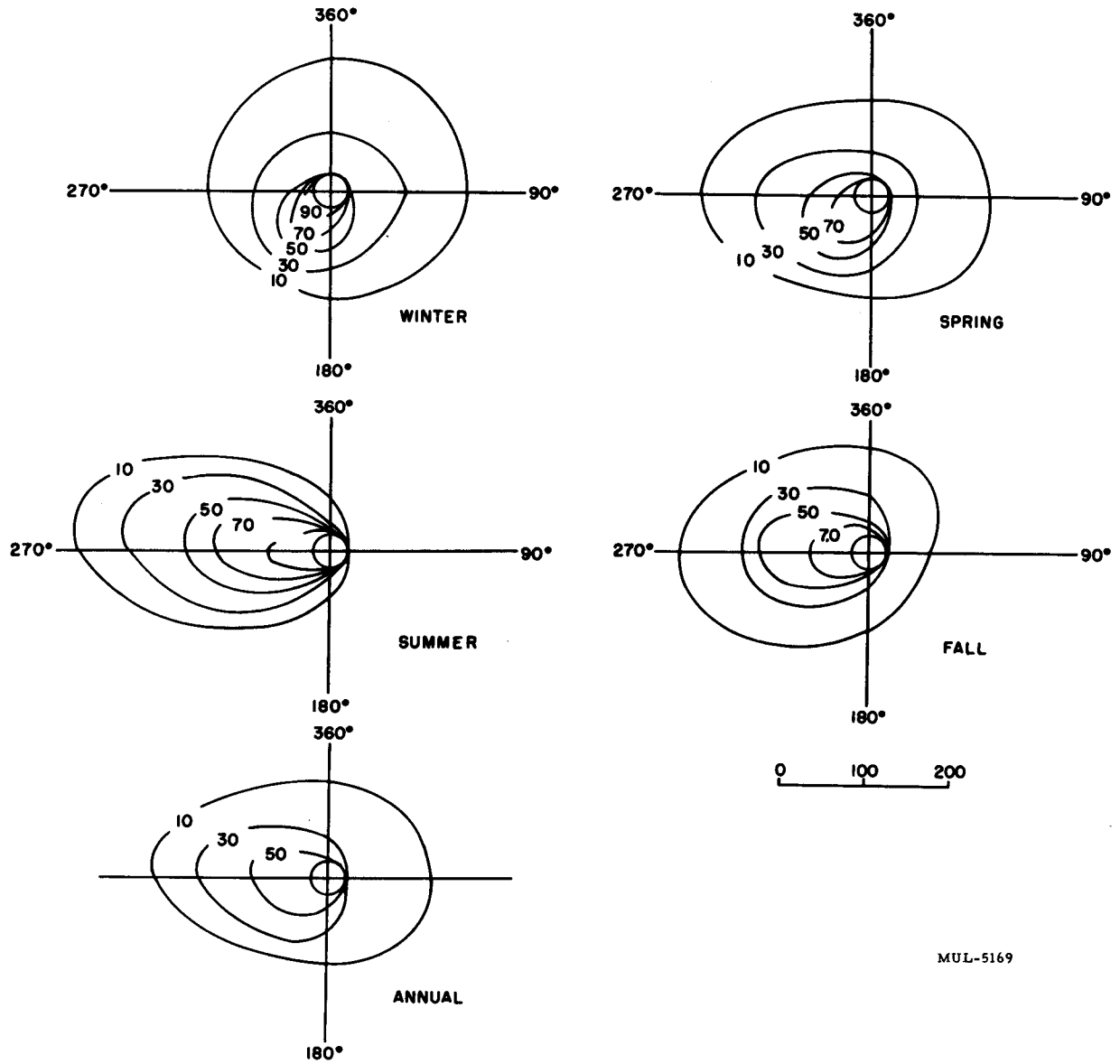
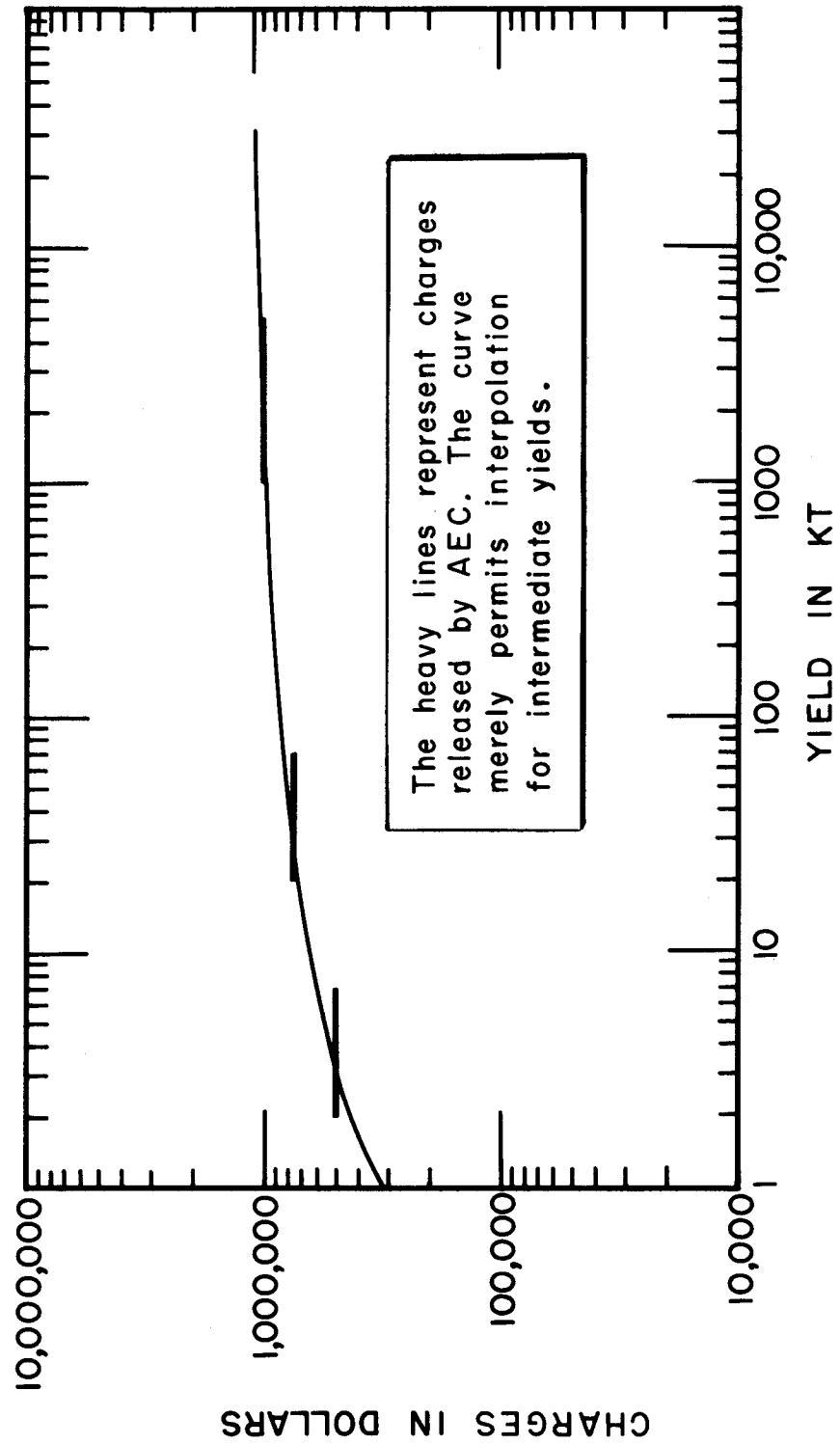


Fig.16. Fallout Probability, Albbrook Field, Canal Zone.



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Figure 17.

CONTAMINATION PROBLEMS

by

A. V. Shelton (UCRL)

I am going to describe a representative fallout pattern for surface bursts such as have been discussed in connection with the digging of a long channel and try to relate the predicted radiation intensities to their effects on populations, so as to give some idea of permissible limits on radiation dose and thus on explosive fission yield. In addition, we will look briefly at intensities to be expected at the crater lips, with respect to the difficulties associated with the clean-up and completion of a channel.

As far as the radiation effect on people is concerned, the limiting factor is the external gamma dose rather than the external charged-particle dose or the ingestion of activity. In Nevada test operations the permissible gamma dose off-site is limited to 3.9 r per operation or 5 r per year, with a further limitation for longer time periods. The beta or alpha dose or ingestion effects do not seem to be important at the above levels of gamma dose. Because of the uncertainties in weather and fallout prediction, the permissible forecast dose on people is usually held to 1 r per event. This limit of 1 r forecast dose can reasonably be expected to apply to any native or "off-site" population in the case of detonations for useful purposes in foreign lands.

We will now consider the radiation doses to be expected from the surface detonation of a device with a total yield of 100 kt and a fission yield of 10 kt. For such a detonation under wind conditions that are representative of low-latitude conditions, the effective biological dose at a distance of 180 miles will be of the order of 300 milliroentgens. An array of 17 such devices so placed as to dig a channel one mile long will put a biological dose of 5 r at the distance of 180 miles. The width of the fallout pattern is large compared to the one-mile source length. The area within which the dose is greater than 5 r is of the order of 10,000 square miles, which area must be cleared of people and controlled for some time following detonation.

The accuracies of fallout intensity predictions are such that effects beyond 150 to 200 miles are essentially unpredictable. One does not know to any reasonable reliability either the dose or the location of the pattern beyond such distances. For this reason it is probably mandatory that the

4 r forecast distance not extend beyond this range and, therefore, that any single line of detonations not exceed a fission yield of 150 kt.

If it is desired to fire 15 Mt to dig a 50-mile-long channel and to do it within a short period, i. e., a few months, the devices used should be about 1% "fission." The fission activity will then be of the order of the neutron-induced activity.

The region within a few hundred yards of the crater edge will be at thousands of r per hour at 1 hour for a device which is 10% fission and probably at less than 1000 r/hr for devices which are 1% fission. Decay rates near the crater are such that 10,000 r/hr at 1 hour will decay to 15 r/hr after 1 month and 0.300 r/hr after 1 year. These intensities would require a large clean-up effort or a long waiting period before finishing work could be done on a channel.

The cost of the fallout prediction effort should be of the order of 1 or 2 million dollars for a canal digging operation involving the yields discussed. The largest part of this amount will go into a weather measuring network such as is used in the Pacific Testing Area and without which fallout forecasting would be so uncertain as to be useless.

IV. MISCELLANEOUS APPLICATIONS

SUBSURFACE NUCLEAR EXPLOSIONS FOR SEISMOLOGICAL STUDIES

by

William R. Perret (Sandia Corporation)

Deep underground or underwater nuclear explosions are sources of energy comparable to that released by earthquakes. Such explosions could serve, within certain limitations, as very effective sources of seismic energy for scientific studies of the remote interior of the earth.

Everything known about the interior of the earth except for about 8 to 10 kilometers of the outermost skin, which have been explored by wells and mines, has been derived from either seismology or geodesy. The former derives information on the earth's interior by remote observation of earthquakes; geodesy derives information concerning the shape and distribution of density within the earth by surface observations of gravity, precise surveying, and astronomy. So far, all knowledge of the really deep interior of the earth has depended upon earthquakes. Like most natural phenomena, these have the unfortunate habit of occurring when and where they want to with no regard for times or places of the observers' choosing.

This means that there is never direct knowledge of the position of an earthquake focus or of when it occurred. Earthquake-generated events arrive at observation stations over paths which must be estimated on the basis of estimated properties of the materials along the paths. Both of these estimates must be derived in some degree from the same data. The redeeming features of this whole process lie in the fact that it is a type of boundary value problem which permits solution and that a sufficient number of earthquakes occur to allow a statistical approach to the solution.

Earthquakes have furnished seismological data sufficient to develop a surprisingly detailed picture of the nearly 6400 kilometers of more or less solid earth between the surface and the center. There is a crustal shell about 33 km thick composed of granitic and sedimentary rocks underlain by basaltic rocks; beneath this shell lies a mantle about 2850 km thick of rigid ultrabasic rock, still deeper an outer core about 2200 km thick probably composed of nickel-iron in a fluid (less rigid) state, and finally

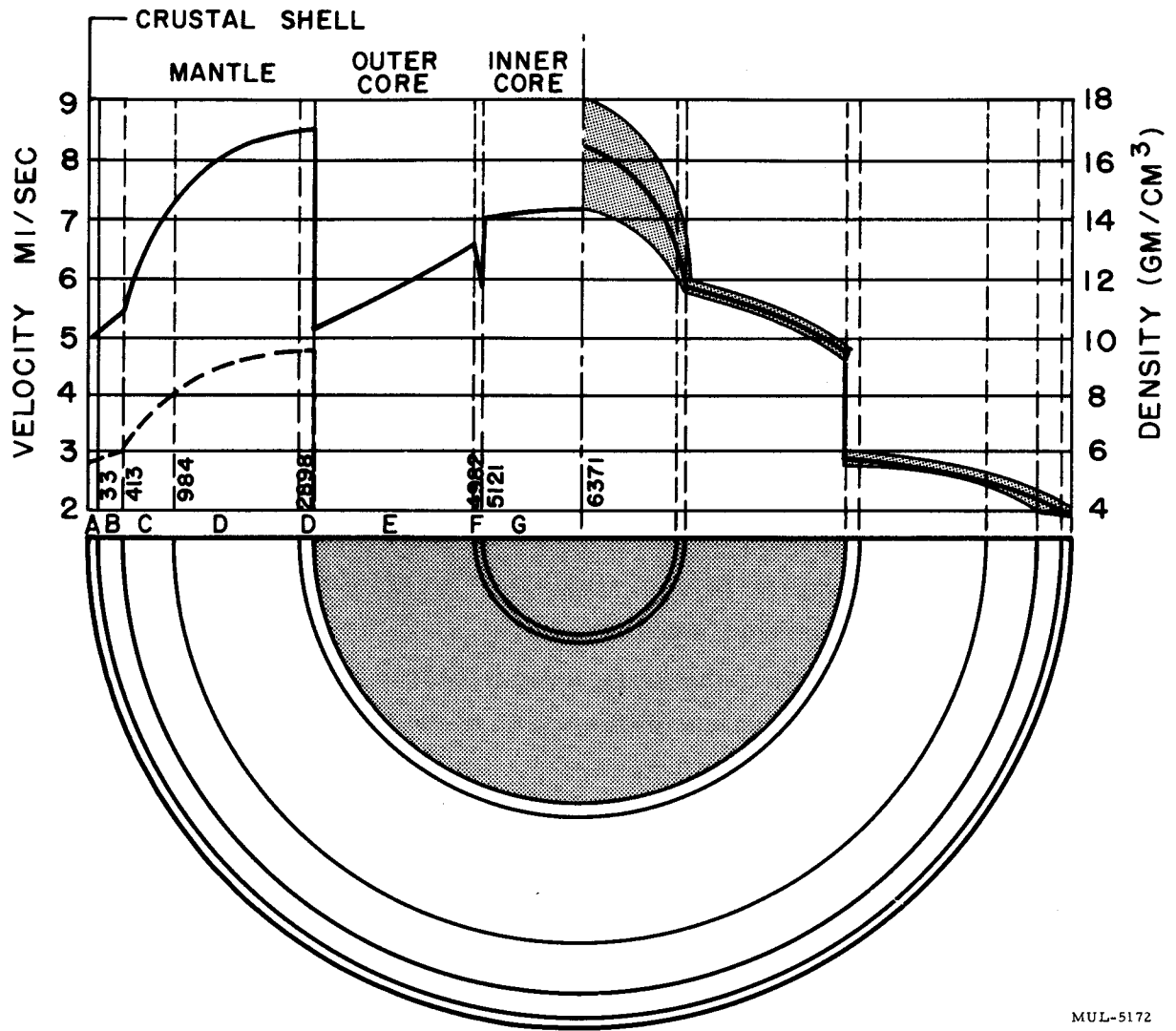
an inner rigid core of nickel-iron or heavier elements of about 1250 km radius. See Fig. 18. However, the precision with which these regions can be defined is effectively limited by the fact that only absolute arrival times, wave forms, and motion of relatively small areas remote from the source are directly observable. Time of initiation, position of the source, and energy released must be deduced from the remotely observed data; independent determinations of seismic paths and material properties along the path are not feasible.

Data from an artificial source can reduce effectively the broad zones of uncertainty inherent in use of earthquake seismology for defining the interior of the earth. High-explosives of relatively low energy release, ranging from a few pounds to 1.375 kilotons (10^{14} to 6×10^{19} ergs) have provided a means for defining the character of the crustal shell and perhaps the outer region of the mantle with improved accuracy because time and place of such explosions are predetermined and precisely defined. But these energies are not generally sufficient for very remote observations and consequently limit the scope of interpretation to shallow characteristics. Nuclear explosives are obtainable with energy content several orders of magnitude greater than chemical explosives. Tens of kilotons of TNT-equivalent explosive energy may be had in readily handled, relatively small packages, and these energies are in the range of mildly damaging earthquakes (10^{21} ergs).

Such nuclear explosions can serve as a source of artificial seismic signals. These signals will be stronger in longitudinal (compressional) wave components and weaker in transverse (shear) waves than earthquakes. However, proper choice of site and depth of burial, coupled with adequate prior warning to seismologists of intent and detonation time, would make a deep nuclear explosion an important tool for seismological study of the interior of the earth.

Considerations for safety of such an explosion resolve into three areas of concern: structural safety of local buildings, contamination of ground water, and triggering of earthquakes either nearby or remote. Rainier event of Operation PLUMBBOB has corroborated predictions and provided a sounder basis for defining criteria for safety.

Safety of dwellings and industrial building must be achieved by remoteness of the explosion site from such structures. Rainier showed that structural



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Fig.18. Cross Section of the Earth.

safety for a 2-kt burst could be anticipated at radial distances greater than two miles. For a contained, 60-kt explosion in a similar environment the safe radius would be somewhat more than five miles.

Ground water contamination from a contained underground nuclear explosion implies that radioactivity residual from the explosion becomes entrained in ground water which forms part of a supply for domestic or industrial use, and that concentration of the radioactivity is sufficient to constitute an appreciable portion of minimum permissible dosage. Again, Rainier experience has verified prediction in that essentially all radioactivity derived from the explosion was trapped in the resolidified glassy residue of molten rock within a radius of 65 feet of the burst point. The transmission of this material to ground water must be by leaching of the very insoluble glassy residues. There was no aquifer in the immediate vicinity of Rainier but the results just described suggest that, in the presence of moving ground water, contamination, if detectable, would have been negligible. There is thus very reassuring evidence that ground water contamination, for an underground nuclear explosion, is not a serious hazard and that it can be minimized by the obvious precaution of choosing sites for underground explosions in areas isolated from usable aquifers.

Finally, the earthquake triggering problem may be answered first by the vast fund of seismological evidence that no natural earthquake has been known to trigger another, and second by examination of the known nature of earthquakes and comparison with corresponding effects of nuclear explosions. Earthquakes usually occur as sudden releases of energy stored up by slowly developing strains across an area of faulting or cracking in the earth's outer crustal shell as large adjacent blocks move relative to each other.

Strains exist in greater or lesser concentration over considerable areas of the fault zone. Where the strains become so great as to develop stresses beyond the shearing strength of the rock, movement to relieve the strains occurs. Such movement is usually in a series of sudden steps, some of catastrophic magnitude, some barely detectable. These are earthquakes. Energies released by single shocks range from insignificant amounts through 10^{21} or 10^{22} ergs deduced from records of the major shocks at Tehachapi, California in 1952 and Dixie Valley, Nevada in 1954 to 10^{23} ergs estimated for the principal shock of the 1906 San Francisco earthquake. The latter

energy is roughly equivalent to that of 2 megatons of TNT.

Sources of earthquake energy are generally extended and relatively deep; they probably extend over areas of several tens of square kilometers of the fault zone at depths of one or more kilometers. Nuclear explosions are essentially point sources of very high energy density. Earthquake sources usually entail large shearing forces, and a major portion of the energy is propagated initially as shear waves. Nuclear explosions develop very high compressive stresses, and mechanical energy is transmitted primarily as compressive waves.

It is conceivable that intentional or fortuitous detonation of a nuclear explosive in a fault zone of high potential strain energy and at a point of incipient shear might precipitate an earthquake. This is, however, a situation far easier to avoid than to achieve. Avoidance requires only that the site for an underground explosion be chosen remote from any region of major existing or active fault zones. Intentional triggering of an earthquake would require (1) prior firm knowledge of the state of strain along an active fault zone, (2) knowledge of the position in the zone, both in depth and laterally, of maximum strain energy and minimum residual strength (that is, the optimum point for energy release), and (3) the capability to place the explosive within effective range of that specific point. Accomplishment of these requirements could perhaps trigger the earthquake but this would not cause an event which would otherwise not occur; it would merely hasten, perhaps by minutes, days, or months, an event certain to occur in the future. But present knowledge and understanding of the intimate processes and conditions germane to incipient earthquakes is hardly adequate to define the first two requirements well enough to permit effective accomplishment of the third.

A nuclear explosion detonated underground under conditions to ensure maximum coupling of energy to the earth and to fulfill safety requirements can contribute effectively to seismology. Optimum contribution requires, in addition to the conditions above, early and widespread announcement to seismologists, through existing international communication channels, of such knowledge as intended time (nearest hour and day), position (nearest minute of latitude and longitude) and approximate energy (order of magnitude). The contribution would comprise two principal sources of new knowledge: (1) precisely fixed end points for travel-time curves and travel-time curves of higher precision, (2) studies of such areas of currently incomplete understanding

as the 20-degree discontinuity and other regions of transition in signal behavior or material characteristics. Results in the first area might contribute only a considerably higher degree of confidence in present travel-time curves, which form the basic tool for interpretation of seismic records; but this would materially advance the science of seismology. In the second area, the 20-degree discontinuity concerns a characteristic type of seismic record discontinuity which has been observed in the region from about 14 degrees to something over 20 degrees of epicentral distance (range from the epicenter in degrees of arc of a great circle). Data from earthquakes are sufficient to establish the discontinuity, but dependence on fortuitous occurrence of proper epicentral distances at fixed seismograph stations has not permitted full definition of the discontinuity nor an understanding of its nature. However, foreknowledge of a nuclear explosion suitably located would permit strategic arrangement of portable observation stations to derive optimum interpretable data for study of the 20-degree discontinuity. Similar facilities would provide for effective study in other areas of interest.

PLUTONIUM BREEDING, COLLECTION OF MATERIALS

by

John A. Wheeler (Princeton University)

Shooting over land has associated with it political problems so the idea was to see what one could do under water. Detonation of TNT underwater produces a film of carbon black on the surface and detonation of Torpex* produces a film of aluminum on the surface. This result proves that under some circumstances one has an automatic collection of the products of the explosion on the surface. One therefore asks himself if he can use a similar principle on a fission bomb shot off under water. The explosion creates an undersea bubble. This bubble goes through the traditional history of a bubble. It oscillates with a period of the order of magnitude of a second. When formed sufficiently deep (5 km) by an explosion small enough compared to 20 kt, the bubble should approach the surface broken up into a million small bubbles and should be absorbed. The hope was that the warm fission products would then all spread out on the surface, dilute with water, and one could then work out a scheme of collection at the surface.

There are two problems, (1) collection and (2) chemical separation. As for separation, if I recall correctly from the work of Perlman and collaborators, U and Pu can be recovered from sea water at concentrations of the order of magnitude of some milligrams per ton of sea water. However, in the meantime one has learned that the story of the disposition of the products is a little different from what was assumed several years ago. The products seem not to rise with the bubble, but to be deposited in the water near the phases of maximum contraction. If this conclusion is confirmed, it suggests use of an undersea explosion in a modified form: not collection at the surface, but collection at the sites of bubble cavitation.

Assume a yield of 17 kilotons at a depth of two kilometers, in other words, a kilogram of material burned with several kilograms of material involved in the pickup of neutrons. One is dealing with a bubble that reaches a size of the order of magnitude of 80 meters in radius at its maximum expansion, which then contracts. As it contracts the upward momentum that

* Main constituents: TNT, RDX, and aluminum.

has been imparted by reason of the large size gets concentrated on a small mass. As the bubble reaches its minimum contraction there is a rapid rise of this small mass. This expansion and contraction repeats, and during each phase of the contraction there is this rapid rise. Pictures of underwater explosions show that at a period of minimum contraction the surface does not have the ideal spherical form, but manifests itself instead by numerous prongs and spikes, due to an instability phenomenon akin to Taylor instability. The concentration of product in these cavitating prongs and spikes can be calculated only to a very rough order of magnitude, which may be badly off. Assume at the phase of maximum contraction that the 80-meter maximum radius has shrunk down to roughly a tenth of its radius, and that this minimum volume is perhaps one-tenth spikes and the other nine-tenths a region in which no fission product is left. I should emphasize that these estimates can be off by several factors of 10 in either direction. Specifically, assume roughly 1000 cubic meters in the spikes where the valuable material has concentrated. Then one estimates of the order of magnitude of 1 gram of material per cubic meter. Soon after the bubble has reached the surface the material left behind in the spikes will be diffused by turbulence. Therefore it has to be collected quickly, so that one can capitalize on the hydrodynamic concentration mechanism before the hydrodynamic diffusion mechanism gets to work.

For the time being, however, I feel we should forget any long-range goal of making an "undersea production breeder." Instead, can one not do something to study, measure, and understand the concentration mechanism? Can one devise an experiment on techniques of collecting material in such regions? The kind of device that one might think about is based on the way that big fishes go around collecting little fishes. Envisage a motor-driven submarine with a volume capacity of the order of magnitude of 1000 cubic meters, filled with sea water, and also a plastic bag. The plastic bag opens to the sea through long flexible rubber arms. It turns inside out and expels the original sea water content as it collects the fission debris. This "gobbler" is located several hundred meters from the site of the explosion and rushes to the spot immediately after the bang. The feelers reach out and their tips are attracted either by the light that is given out from the fission products or by the gamma rays themselves as they approach points of high fission-product concentration. These feelers suck up selectively

this part of the liquid. As this material is sucked in, it displaces the diaphragm which gradually moves back. It appears important to study by such means or otherwise the existence of regions of high fission-product concentration, especially on shots of relatively modest size. Only then can one tell if one can hope someday to capitalize on the hydrodynamic concentration mechanism.

If it is true, as has been heard, that the first contraction phase is one where the major part of the products are deposited, then one would not have to worry about shooting it off so deep that the bubble, by the time it gets to the surface, has broken up into a million small bubbles. One would have no worry that the bulk of the valuable activity would be lost into the atmosphere. Then one might consider going to a thermonuclear weapon with its high breeding efficiency.

ROCKET PROPULSION BY MEANS OF NUCLEAR EXPLOSIONS

by

Thomas Wainwright (UCRL)

The idea of accelerating missiles by means of nuclear explosions has been discussed previously by various authors.^{1, 2}

In what follows we shall be thinking of the final stage of a rocket which has been lifted by means of booster stage to an altitude of the order of 80,000 ft and has been engulfed in the fireball caused by a nuclear explosion. Exhaust material contained in the rocket is assumed to have had its temperature raised to that of the fireball and to be ejected with isothermal sound velocity. The table below lists, for various exhaust materials and various exhaust temperatures, the fraction of the total mass of the rocket which must be ejected in order to impart the velocity of 1.65×10^6 cm/sec to the residue. At this velocity the rocket can leave the earth and escape the solar system in the plane of the earth's orbit.

Exhaust material	Exhaust Temperature			
	0.5 ev	4 ev	10 ev	50 ev
H	0.91	0.46	0.31	0.15
CH	0.996	0.81	0.56	0.26
N	~1	0.96	0.81	0.40

Some of the difficulties and disadvantages of this scheme are apparent. The outside shell of the rocket will be exposed to a high pressure and also a high temperature, which will result in considerable ablation of material from the surface. This will require that the shell be strong and thick and also

¹ J. von Neumann and E. Teller, Classified Report UCRL-4412, Nov. 1954.
² C.J. Everett and S.M. Ulam, Classified Report LAMS-1955, Aug. 1955.

heavy so that there is some degradation of the advantageous mass-ratio allowed by the high exhaust velocity. Since the rocket spends only a rather short time in the fireball, the acceleration will have to be high. For example, if the rocket is to achieve a velocity of 1.65×10^6 cm/sec while traversing the fireball of 3 km in diameter, the acceleration (assumed constant) will be 4600 g, and the time spent in the fireball will be 0.36 seconds. This requires that only rather rugged instruments be aboard the rocket. Perhaps not so apparent is the difficulty of arranging to have the exhaust material irradiated from the time of interest.

Experimental and theoretical studies indicate that in order to irradiate large masses of the exhaust material it would be necessary to have fireball temperatures considerably higher than the few electron volts ordinarily achieved.

THE FEASIBILITY OF PRODUCING DIAMONDS BY NUCLEAR EXPLOSIONS

by

Ivan F. Weeks and Roy W. Goranson (UCRL)

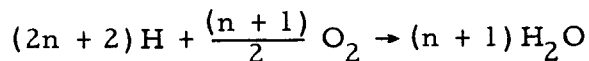
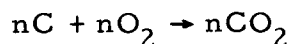
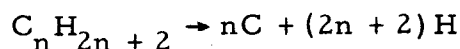
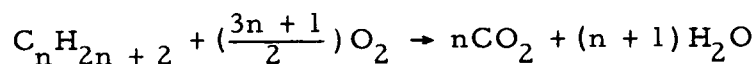
Introduction and Summary

During the course of this Symposium suggestions were made that the high pressures associated with nuclear explosions might be used to produce diamonds. The purpose of this paper is to examine the chemical physics of diamond, graphite and other carbonaceous materials. The experimental evidence on the laboratory production and conversion of diamonds is reviewed. A simple rate theory argument is presented which appears to be consistent with the experimental evidence. The application of the rate theory to the utilization of nuclear explosion pressures in converting carbon to diamond shows this peaceful application to be very impractical. It should be noted, however, that the direct conversion of graphite to diamond is difficult in any case if not impractical.

The Properties of Carbon-Carbon Bonds

Let us examine the bond strengths between the carbon-carbon bond in saturated hydrocarbons. The complete dissociation of a hydrocarbon C_nH_{2n+2} into $nC + (2n + 2)H$ atoms, involves the breaking of $(2n + 2)CH$ bonds and $(n - 1)CC$ bonds. The measurement of the heats of combustion permits an evaluation of the carbon-carbon bond strength.

Consider the reactions



Let the bond energy of the CH bond be denoted by $E_{(CH)}$ and that of the carbon-carbon bond by $E_{(CC)}$. In addition, let $E_{(CO_2)}$ be the energy released in the reaction $C + O_2 \rightarrow CO_2$, and $E_{(H_2O)}$ be the energy released in the reaction $2H + 1/2 O_2 \rightarrow H_2O$. The energy released by the oxidation E_n is equal to $nE_{(CO_2)} + (n+1)E_{(H_2O)} - (n-1)E_{(CC)} - (2n+2)E_{(CH)}$. Let us assume the E_{CH} is independent of n . Then the bond energy $E_{(CC)}$ is a function of n only and can be determined by subtracting the heats of combustion of neighboring hydrocarbons, that is,

$$\frac{(n+2)}{2} E_n - \frac{(n+1)}{2} E_{n+1} = E_{(CC)} - 1/2 E_{CO_2} = B_n.$$

The heats of combustion of various saturated hydrocarbons and the corresponding B_n 's are given in the following table:

Table IX Bond Energy of Normal Saturated Hydrocarbons
(E_n in kcal per mole)

n	E_n	$-B_n$
1	212.80	53.62
2	372.82	50.26
4	687.65	49.95
6	1002.57	49.72
10	1632.34	49.75
14	2262.11	49.74
18	2891.88	49.74
Diamond		47.24
Hydrogen-free anthracite		48.128
Graphite		46.978

In the diamond, each carbon atom is bonded to four carbon atoms, and since each bond has two carbon atoms associated with it there are twice as many bonds as atoms. Let the heat of combustion of diamond be denoted by $-2E_d$. One has for diamond the following equation

$$-2E_d = -2E_{(CC)} + E_{(CO_2)}$$

The structure of diamond is shown in Fig. 19 titled "Crystal Structure of Diamond." In diamond one finds a regular spacing of the carbon-carbon bonds at 1.54 Å. The symmetrical property of the carbon-carbon atoms in diamond is responsible for the low compressibility and great hardness of diamond. The large separations associated with the C-plane in graphite have disappeared. Hence, it is apparent that for the conversion of graphite to diamond a great deal of reorientation of the graphite lattice is necessary. The carbon-carbon bond links in the a-plane of graphite could be distorted to match the appropriate locations in the diamond lattice by the use of temperature. It is also apparent that the use of pressure would tend to collapse these distances. In Table IX there is an entry for "Hydrogen-free anthracite coal". The heats of combustion of anthracite coal with varying amounts of hydrogen present were determined, and the heat of combustion of hydrogen-free anthracite was obtained by extrapolation. If one extends the argument on the carbon-carbon bond lengths, it is apparent that one would have to consider the hydrogen-free anthracite coal as having a bond length which is longer than that existing in the diamond or in the corresponding saturated hydrocarbon series. The stable form for this carbon is graphite at low pressures and diamond at high pressures. Hence, following up the previous argument there would be a decrease in volume on going from anthracite to graphite. Hence, pressure would tend to decrease the volume and thereby increase the probability of forming graphite. However, the temperature effect is in the opposite direction.

Experimental Facts

General Electric¹ has reported that at a pressure of 135,000 kg/cm² and a temperature of 1033°K they can produce about 2 carats of diamonds in 2 minutes. Norton Co.² has been able to produce diamonds occasionally at about 45,000 kg/cm² and 1000°K.

Neither of them started with ordinary graphite. In fact, from simple theoretical considerations it appears to be very difficult to produce diamonds from ordinary graphite. G.E. experiments have shown that up to temperatures as high as 3000°C and pressures up to 100,000 atmospheres, that diamond was not formed from graphite.

¹ General Electric (private communication).

² Norton Co. Worcester, Mass., (private communication).

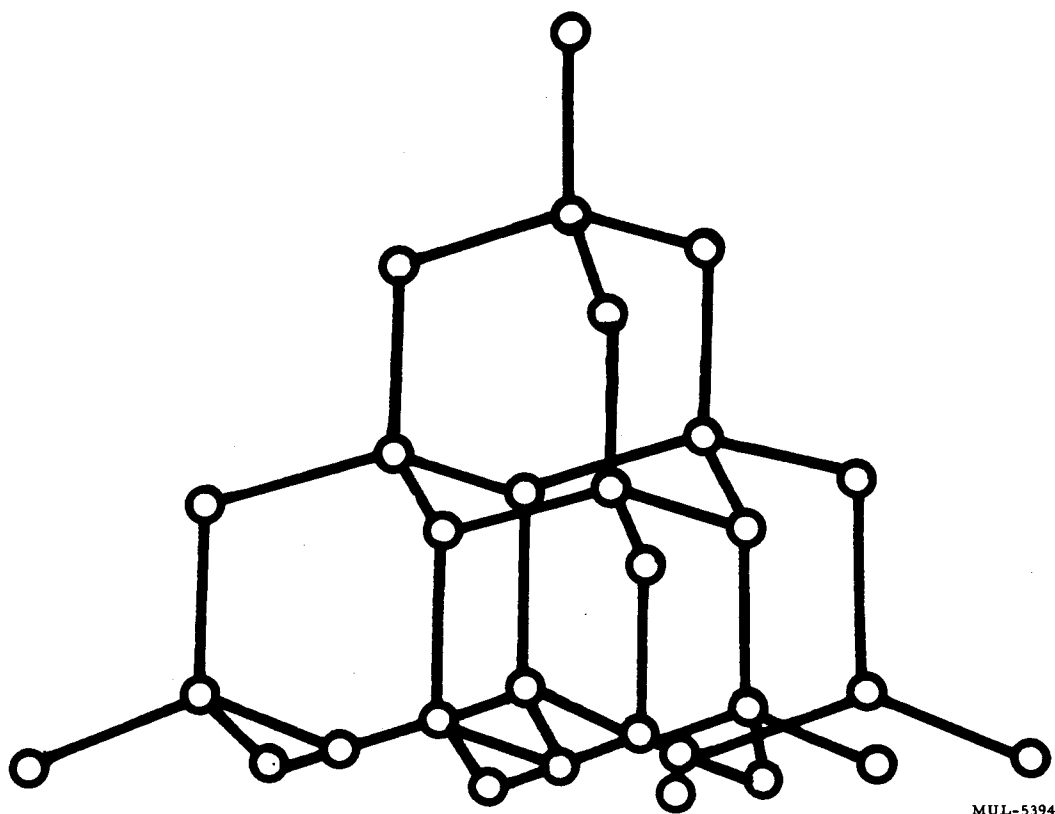


Fig.19. Crystal Structure of Graphite.

The sublimation energy of graphite is $2E_{(CC)}$. The heat of combustion of diamond is 94.50 kcal which leads to a value of 47.25 kcal/mole for the B_n for diamond. It should be noted that the heat of combustion of graphite is 94.05 kcal per mole. Hence, the transition of 1 gram atom of diamond at 25°C to graphite at 25°C involves a decrease of 0.45 kcal/mole in heat content.

Based on the assumption of a constant value of E_{CH} , it can be readily seen that carbon-carbon bond energy in saturated hydrocarbon is constant for all but very low values of n . Electron diffraction data show an interatomic distance of 1.54 Å for these carbon-carbon bonds. The carbon-carbon interatomic distance in diamond is 1.542 Å.

Assuming the energy of a single bond is 3 electron volts, the energies of a double bond and the triple bond are 5.28 and 7.08 ev, respectively. The interatomic distances associated with the single, double and triple bonds in carbon-carbon are 1.54 Å, 1.33 Å and 1.2 Å, respectively. The length of the carbon bond and the bond order are shown in Fig. 20a.

In this curve are shown also the bond lengths for graphite, benzene and dicarbon gas (C_2). Dicarbon has a heat of association of 162 kcal/mole and its bond order is of the order of 2. The figure also shows that the carbon-carbon energy in graphite is 4.6 ev or 104 kcal/mole. Diamond is represented by a single carbon-carbon bond. It is apparent that a very high activation energy is associated with the reaction rate of graphite→diamond.

The crystal structure of graphite is shown in Fig. 20b. The a-plane is reminiscent of a very gigantic hydro-carbon molecule of the aromatic series. The carbon-carbon length in benzene is 1.39 Å whereas in graphite it is 1.42. It is not surprising that the molecular orbital theory of graphite shows the same type of π orbitals of electrons as is found in the theory of the structure and stability of benzene. It is well known that these mobile electrons are associated with the conductivity of metals. In graphite one has a partial metal, in that there is electrical conductivity along the basal plane. It should be noted that the basal planes are separated by a considerable distance. These distances are so large that the only explanation can be that they are held together by Van der Waal's forces. It should also be noted that the carbon atoms on one plane, in respect to the other plane, are not all directly above one another. The separation between the similar layer structures is known as the c-plane, and has a separation distance of 6.7 Å.

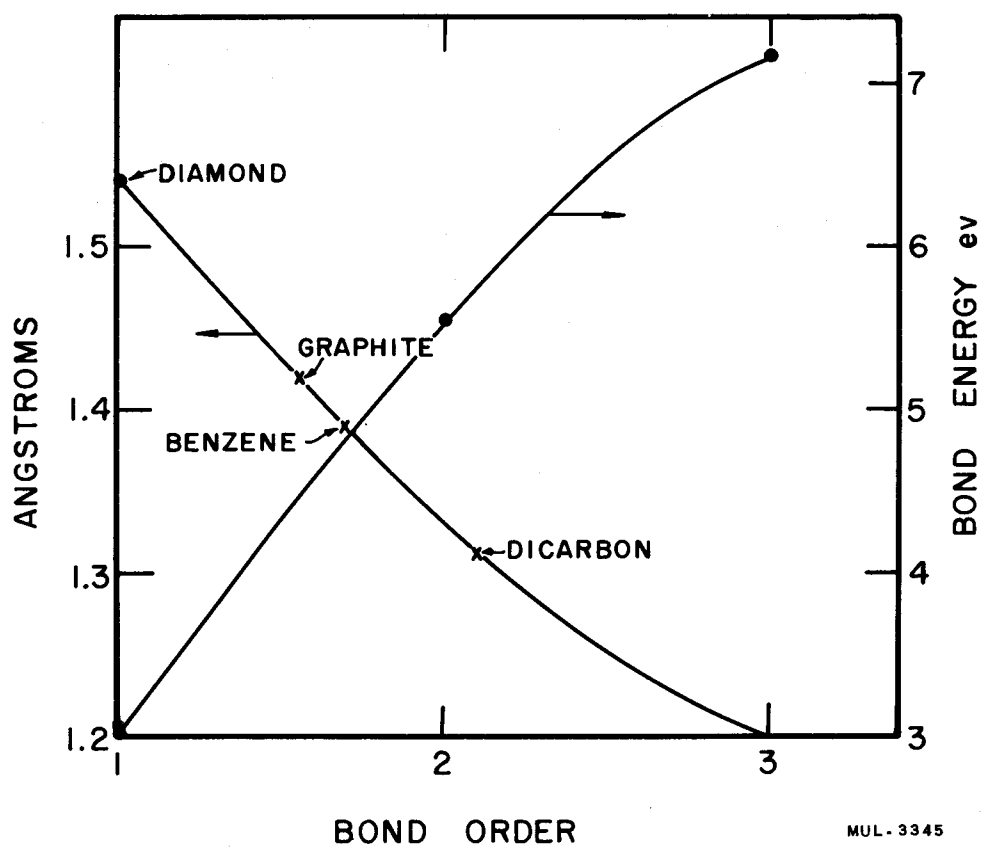


Fig.20a. Bond Length and Bond Energies in Carbon-Carbon Bonds.

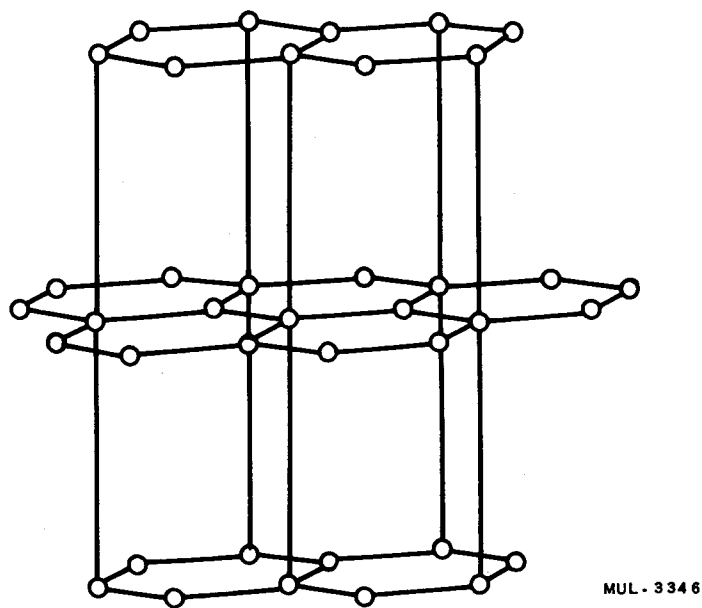


Fig.20b. Crystal Structure of Graphite.

The two operating points of G.E. and Norton Co., are reproduced on the graphite-diamond phase diagram. (See Fig. 21 .) The significance of the higher pressure at which G.E. operated will be discussed below.

Bridgman³ applied pressures up to 30,000 atmospheres to graphite seeded with diamonds and then raised the temperature to $3000 \pm 500^\circ\text{C}$. At a pressure of 15,000 atmospheres the conversion of graphite to diamond was 100% but at 30,000 atmosphere it was essentially nil.

Let us now examine the elementary theory in order to determine the feasibility of obtaining diamonds by means of nuclear explosions in the light of experimental facts at our disposal.

Phase Diagram of Diamond-Graphite

The diamond-graphite phase equilibrium diagram has been computed by a number of people, including Goranson⁴ (1940), Liljeblad⁵ (1955), Berman and Simon⁶ (1955) and General Electric. Liljeblad's curve differs most violently from the others in that the slope of $(dP/dT)_{\Delta F = 0} = 0$ at about 65,000 atmospheres and 2500°K . He also indicates that at higher temperatures the slope becomes negative. The equilibrium curves of Goranson and Berman and Simon are essentially in agreement. The G.E. curve lies at somewhat higher pressures for corresponding temperatures.

It should be noted that phase diagrams represent matter in thermodynamic equilibrium. Based on thermodynamics, diamond should not exist. Consequently, one must look to reaction rate theory to explain the existence, as well as the formation of diamonds.

Elementary Rate Theory

The reaction rate constant can be written as

$$k_r = \kappa \left(\frac{kT}{h} \right) e^{-\Delta F^*/RT} ,$$

³P.W. Bridgman, Jour. Chem. Physics, 15, 92 (1947).

⁴R.W. Goranson, Sci. Monthly, 51, 528 (1940).

⁵R. Liljeblad, Arkw. for Kemi, 8, 423 (1955).

⁶R. Berman and Sir Francis Simon, Zeit fur Electrochemie 59, 333 (1955).

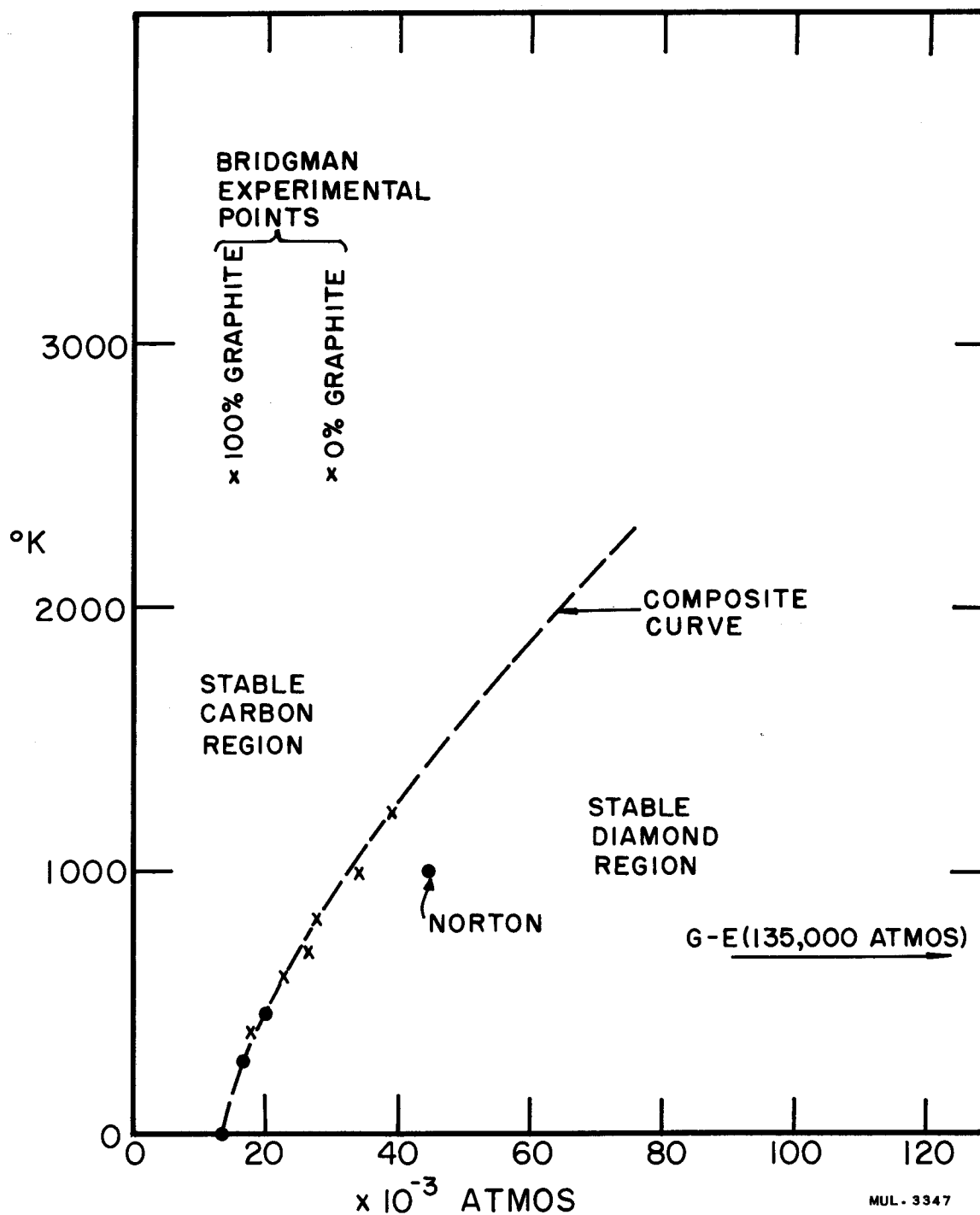


Fig.21. Graphite-Diamond Phase Diagram.

where κ = transmission coefficient
 T = temperature in $^{\circ}\text{K}$
 h = Planck's constant
 R = gas constant
 k = Boltzman constant

The free energy of the reaction can be written as

$$\Delta F^* = P\Delta V^* - T\Delta S^* + \Delta E^*,$$

where ΔE^* is the reaction energy between the initial and activated state,
 ΔV^* is the volumetric difference between activated and initial states,
 ΔS^* is the entropy difference.

Then the reaction rate k_r can be represented by

$$k_r = \kappa \left(\frac{kT}{h} \right) e^{-(P\Delta V - T\Delta S + \Delta E)/RT}$$

or

$$k_r \propto T e^{-P\Delta V/T}.$$

If $\Delta V > 0$ an increase of pressure would decrease the rate and a high temperature would be necessary to override the pressure effect. If $\Delta V < 0$ the rate would increase exponentially with pressure, whereas temperature would tend to decrease it.

Application of Reaction Rate Theory

Let us now consider the thermodynamic relationship between free energy and the equilibrium constant,

$$\Delta F = RT \ln K_p.$$

The equilibrium constant is related to the rates of reaction by

$$K_p = \frac{\text{rate forward}}{\text{rate backward}}.$$

Let us consider the reaction $\text{graphite} \rightleftharpoons \text{diamond}$.

This is consistent with the requirement of a volumetric expansion of the diamond lattice to reach the activated state; e.g., in first-order reactions one usually assumes as a first approximation that the bonds are stretched by 10%.

Hence, the volume of the activated state is greater than $3.42 \text{ cm}^3 \text{ mole}^{-1}$, the molal volume of diamond. The molal volume of graphite is $5.35 \text{ cm}^3 \text{ mole}^{-1}$. For convenience let the molal volume of the activated complex be $4 \text{ cm}^3 \text{ mole}^{-1}$. The equilibrium constant can now be expressed as

$$\begin{aligned} \frac{\text{rate graphite to diamond}}{\text{rate diamond to graphite}} &= \frac{e^{-P\Delta v^* - \Delta E^* + T\Delta S^*}}{e^{-P\Delta v^{**} - \Delta E^{**} + T\Delta S^{**}}} \\ &= \exp -P(-1.35 - 0.58) + T(\Delta S^* - \Delta S^{**}) - \Delta E^* + \Delta E^{**} \end{aligned}$$

Because of the greater order of the diamond with respect to graphite, we conclude that the entropy difference in the above expression is positive. Hence, neglecting the small factor associated with the ΔE , we have at equilibrium

$$e^{P - T\Delta S} = 1 ,$$

The above equation is consistent with the thermodynamic calculation of the phase diagram.

The pressure for the G. E. and Norton operations was applied essentially isothermally but the G. E. operating pressure was about three times that of Norton which would give them a reaction rate which was thirty times that of Norton.

During the Symposium there were many comments to the effect that one should try to form diamond by means of a Hugoniot shock or shocks. The difficulty here is that a high pressure produced by this means is also accompanied by a high temperature. For example,

$$\frac{\left(e^{P/T} \right)_{\text{G. E.}}}{\left(e^{P/T} \right)_{\text{shocks}}} \approx 1 ,$$

for shocks from 0.1 to 1 megabars. It is not feasible to operate with shocks of 0.4 mb or higher since on release of pressure the temperature is still high enough to burn the diamond back to graphite. Furthermore, the duration of a Hugoniot shock is of the order of a few microseconds, whereas the diamond formation time of G. E. is about 2 minutes. This is a factor in rate of 10^8 in their favor.

It is very tempting to consider compressing radiation-damaged graphite in which carbon atoms have been displaced from the a-plane interstitially into

the c-plane. If sufficient carbon atoms have been displaced, then pressurizing the resultant carbon sufficiently might induce the formation of a diamond lattice.

In addition, it should be noted that experimentors at Harwell have subjected graphite to a hydrostatic pressure of 17,000 atmospheres and then irradiated it with neutrons from a pile. Their pressure was too low to form diamond and they stated that they will repeat the experiment at higher pressures. Linlor has independently considered carrying out such an experiment at a pressure of about 30,000 atmospheres. A flux of 10^{14} 2-Mev neutrons per cm^2 per second would cause about $\frac{200 \times 10^4}{25} \times 10^{14} = 4 \times 10^{18}$ carbon displacements per cm^3 per second for 100% efficiency. This would amount to about 1/6 mole of displaced carbon atoms per day which, if converted to diamond, would consist of 10 carats.

CONCLUDING REMARKS

by

Harold Brown (UCRL)

Without trying to summarize all the things that have been mentioned or to assess their relative importance, I would like to make some observations on points which have been emphasized during the meeting.

The first point concerns the necessity for nuclear explosives having low fission-to-fusion ratios, but I think that it is more general than that. A number of the suggestions imply that quite a bit can be done by the Laboratories to gain special effects of one kind or another which have relevance for industrial applications. These things would not ordinarily be considered in connection with military specifications and, by bringing up the question, I hope that the Laboratories have been encouraged to investigate some of these different effects. I agree that devices with low fission-to-fusion ratios have been most constantly and universally stressed here. The idea of making them with very much lower fission-to-fusion ratios than we have been thinking about is one that the Laboratories should take to heart.

The second point relates to the scientific use of nuclear and thermonuclear explosions. In this connection, Sandia Corporation has offered some very specific experiments which might be used during the International Geophysical Year. There may be some argument as to how much will be learned or what experiments should be performed, but it seems to me that this is an appropriate idea for the General Advisory Committee to back.

A third point is that, considering how many weapons, devices, and experiments have been fired, it is remarkable how little we know about the effect of nuclear explosions on any environment but air. The air seems to be a region where there is least industrial or scientific interest, except for the higher altitudes. There has been one underwater shot and, we hope, the first completely underground shot will be made this year. A large number of other environments should be studied.

An additional point is that there is some kind of public relations problem here. In the last 12 years all kinds of phobic public reactions have been built about nuclear bombs, some of them rightly so. (A nuclear war is indeed something to worry about.) The industrial use of nuclear explosives could provide a fine opportunity for people to gain a more rational viewpoint. Just how one dissipates the current backlog of public fear and lack of confidence I do not know, but I do think that people with responsibilities of classification and public relations in the Commission must consider, if anything is to come out of this at all, just what they are going to do about public attitudes in this matter.

Another important point is that although some of the material relevant to industrial uses is in a weapons-design category, much of it is not. We should try perhaps to arrange a new category which covers the industrial uses of such devices while excluding the truly sensitive area of weapons design. A very large part of what we have talked about is in the category of weapons-effects tests, which are really universally known insofar as they are known at all.

Finally, I would like to say that although I expected enthusiasm I am really somewhat surprised that there were so many different topics and so much interest generated among so many people, both before the meetings and even during the meetings. I know there were some people who came here and are leaving unconvinced that any of this is useful, but I think that everybody is convinced that it is interesting. I think that the discussions may now have proceeded to the point where, after combing over the results of the meeting, we may decide that there is really a program here. There is no point in discussing it further until somebody does some work on these or other ideas. The only way to get some work done is to have a group of some number, such as 10 or 20 people, thinking about it for 6 months or a year, picking out the good ideas, and working them out in some detail.

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